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SUITABILITY STUDY OF THE CITY ENERGY ANALYST SOFTWARE IN THE BRAZILIAN CONTEXT

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2024

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SUITABILITY STUDY OF THE CITY ENERGY ANALYST SOFTWARE IN THE BRAZILIAN CONTEXT

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Supervisor: Prof. Dr. Rejane Magiag Loura

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DEDICATION

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It is the end of this chapter. The book, however, has just begun.

"Cities have the capability of providing something for everybody, only because and only when they are created by everybody."

(Jane Jacobs)

RESUMO

Simulações computacionais são ferramentas poderosas para tomada de decisões em projetos de edificações e urbanos, permitindo analisar dados quantificáveis e estudar cenários atuais e futuros. Quando aplicada às cidades, é possível observar os impactos em escala coletiva, além dos desafios e forças da realidade local. Outro aspecto crucial a ser considerado com o crescimento urbano é sua demanda energética, conexão esta que atualmente não é feita de forma efetiva no Brasil, já que as legislações energéticas estão em escala federal e as urbanas, na municipal. Uma forma de trabalhar ambas simultaneamente é através do Planejamento Energético Urbano e, nesse contexto, simulações são fortes aliadas. Este trabalho analisa a viabilidade de aplicação do software de simulação energética City Energy Analyst (CEA) em cenários urbanos de Belo Horizonte e Matozinhos, destacando potenciais e limitações de um software feito para realidades distintas das de nações em desenvolvimento. A pesquisa também traz como produto a criação da primeira base de dados brasileira para o CEA, adaptada às condições urbanas e energéticas das cidades estudadas e outros municípios semelhantes. Além de uma revisão teórica embasando os principais pilares da pesquisa, esta foi dividida em três etapas: uma introdução teórico-prática ao CEA; o estudo da base original do software para criação da versão brasileira, e a fase de simulações com ambas as bases para comparar performances. Os resultados mostraram o potencial do CEA no Brasil. Entretanto, cenários locais cruciais não foram incluídos na base brasileira e nas simulações devido à atual limitação do software em interpretá-los. A pesquisa usa sua abordagem para contribuir no debate sobre a importância do planejamento energético urbano e apontar as forças de incluir ferramentas digitais no mesmo, identificando desafios e oportunidades de adaptação do software para contextos como o brasileiro. Além disso, seus resultados servem para enfatizar a necessidade de softwares de simulação urbana incorporarem diversas realidades para enriquecer debates sobre temas como descarbonização e transição energética. Além da base brasileira, este trabalho produziu um vídeo educacional bilíngue destinado a gestores públicos e urbanistas; originou uma disciplina de graduação na UFMG e gerou um minicurso no evento científico ENSUS, em agosto de 2024.

Palavras-chave: Simulações computacionais; Planejamento Energético Urbano; base de dados.

ABSTRACT

Computer simulations are powerful tools for decision-making processes in building and urban projects, allowing the analysis of quantifiable data and the study of current and future scenarios. When applied to cities, it is possible to observe impacts on a collective scale, as well as the challenges and strengths of the local reality. Another crucial aspect to consider with urban growth is its energy demand, a connection that is currently not effectively addressed in Brazil, as energy regulations are at the federal level and urban legislations, at the municipal sphere. One way to address both simultaneously is through Urban Energy Planning and, in this context, simulations are strong allies. This study analyzes the suitability of applying the City Energy Analyst (CEA) to Brazilian urban scenarios in Belo Horizonte and Matozinhos, highlighting the potential and limitations of a software designed for realities different from those of developing nations. The research also results in the creation of the first Brazilian CEA database, adapted to the urban and energy conditions of the studied cities and other similar municipalities. In addition to a theoretical review supporting the main pillars of the research, this study is divided into three stages: a theoretical-practical introduction to the CEA; the study of the software's original database to create its Brazilian version, and the simulation phase using both databases to compare performances. The results demonstrated the potential of CEA in Brazil. However, crucial local scenarios were not included in the Brazilian database and simulations due to the current limitations of the software in interpreting them. The research uses its approach to contribute to the debate on the importance of urban energy planning and highlight the strengths of including digital tools in this process, identifying challenges and opportunities for adapting the software to contexts like the Brazilian one. Additionally, its results emphasize the need for urban simulation softwares to incorporate diverse realities to enrich discussions on topics such as decarbonization and energy transition. Besides the Brazilian database, this work produced a bilingual educational video aimed at policy makers and urban planners; originated an undergraduate module at UFMG and created a mini-course at the scientific event ENSUS, that took place in August 2024.

Keywords: Computer simulations; Urban Energy Planning; databases.

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LIST OF ABBREVIATIONS AND ACRONYMS

ABNT - *Associação Brasileira de Normas Técnicas* (Portuguese)

a.m. - *Ante meridien* (Latin), “before noon”

ANEEL - *Agência Nacional de Energia Elétrica* (Portuguese)

AR5 - Assessment Report 5

AR6 - Assessment Report 6

ASHRAE -American Society of Heating, Refrigerating and Air-Conditioning Engineers

BEM - Building Energy Modeling

BEN - *Balanço Energético Nacional* (Portuguese)

BR - Brazilian database (CEA)

CEA - City Energy Analyst

CEFET-MG- *Centro Federal de Educação Tecnológica de Minas Gerais* (Portuguese)

CH - Swiss database (CEA)

CO_2 - Carbon dioxide

CO_2e20 - Carbon Dioxide Equivalent on a 20-year horizon

COVID-19 - Coronavirus Disease 2019

CTIT - *Coordenadoria de Transferência e Inovação Tecnológica* (Portuguese)

ENTAC - *Encontro Nacional de Tecnologia do Ambiente Construído* (Portuguese)

EPD - Environmental Product Declaration

EPE - *Empresa de Pesquisa Energética* (Portuguese)

EPW - EnergyPlus Weather File

ET - Evacuated tube

ETH - *Eidgenössische Technische Hochschule* (German)

GDP - Gross Domestic Product

GHG - Greenhouse gas

GW - Gigawatt

H - Hour

UBS - *Unidade Básica de Saúde* (Portuguese)

HVAC - Heating, Ventilation and Air-Conditioning

IBGE - *Instituto Brasileiro de Geografia e Estatística* (Portuguese)

ICLEI - International Council for Local Environmental Initiatives

IDSC - *Índice de Desenvolvimento Sustentável de Cidades* (Portuguese)

IEA - International Energy Agency

ISO - International Organization for Standardization

INI-C - *Instrução Normativa Inmetro para a Classificação de Eficiência Energética de Edificações Comerciais, de Serviços e Públicas* (Portuguese)

INI-R - *Instrução Normativa Inmetro para a Classificação de Eficiência Energética de Edificações Residenciais* (Portuguese)

INMET - *Instituto Nacional de Meteorologia* (Portuguese)

INMETRO - *Instituto Nacional de Metrologia, Qualidade e Tecnologia* (Portuguese)

IPCC - Intergovernmental Panel on Climate Change

$KgCO_2/m^2$ - Kilos of carbon dioxide per square meter

kgCO2eq - Kilos of carbon dioxide equivalent

$KgCO_2$/US$ppp - Kilos of CO_2 per U.S. dollar Purchasing Power Parity (GDP)

kW - Kilowatt

kWh/m^2 - Kilowatt hour per square meter

kWh/m^2.yr - Kilowatt hour per square meter year

L - Liters

LED - Light-emitting diode

L/sq m - Liter per square meter

LPG - Liquefied petroleum gas

Mi - Million / millions

mm - Millimeter

MME - *Ministério de Minas e Energia* (Portuguese)

$MtCO_2$-eq - Million-ton of carbon dioxide equivalent

Mtep - Million-ton of Petroleum Equivalent

MULTI_RES - Multi-family residence

MW - Megawatt

MWh/yr - Megawatt hour per year

NBR - *Norma Brasileira* (Portuguese)

PBH - *Prefeitura de Belo Horizonte* (Portuguese)

p.m. - *Post meridien* (Latin), “after noon”

PMV - Predicted Mean Vote

PR_SCHOOL - Primary school

PV - Photovoltaic

PVT - Photovoltaic thermal

RMBH - *Região Metropolitana de Belo Horizonte* (Portuguese)

SBSE - Society of Building Science Educators

SDGs - Sustainable Development Goals

SG - Singaporean database (CEA)

SIN - *Sistema Interligado Nacional* (Portuguese)

SINGLE_RES - Single-family residence

tCO_2e - Tons of Carbon Dioxide Equivalent

TWh - Terawatt hour

UBEM - Urban Building Energy Modeling

UEP - Urban Energy Planning

UFMG - *Universidade Federal de Minas Gerais* (Portuguese)

UN - United Nations

UV - Ultraviolet

°C - Degree Celsius

°F - Degree Fahrenheit

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1. INTRODUCTION

Computer simulation is a practical and powerful tool in the phases of both building and urban planning, since they take several aspects - some of them defined by regulations - into consideration that can affect positively or negatively the studied object. This tool also offers the possibility of analyzing quantifiable data and visualizing different scenarios simultaneously, both in the present and future, helping build the decision making process on a logical and fact-based foundation.

When this strategy is applied specifically to the urban level, it is possible to see impacts on a collective scale while also having the opportunity to reflect on the strengths and challenges the local urban reality offers and preview forms to maximize the former while tackling the latter. Computer simulations highlight in a clear way how crucial it is not only to consider the characteristics of each building, but also to include their surroundings in the investigation, since the urban density impacts considerably relevant variables such as ventilation, incident solar radiation, shading, the potential of on-site energy production, among others. In Brazil, applying computer simulations to the urban scale can also potentially contribute to local legislations, such as the *Plano Diretor*, a mandatory document for cities with over 20,000 people that define requirements and rules to guide their urban development for the next 10 years. The ability of representing present and possible future scenarios through defined parameters can be translated into an evaluation of urban policies that should be either implemented, adapted or discarded from said legislation.

While discussing a city's development and growth, another topic becomes equally relevant and cannot be overlooked: energy. How energy demanding the city is and will be, as well as how to keep it working sustainably for the foreseeable future. The way public policies affect the urban fabric, transportation and energy demand of a city should be taken into account concomitantly and when there is a combination of urban analysis and local energy planning, considering both of their strengths and weaknesses simultaneously, a relatively new concept starts to be addressed: the Urban Energy Planning (or UEP), which will be further discussed in this work. Although being a field with a relatively limited literature nowadays, it is an immensely valuable example of strategy that has gained attention in the last few years (COLLAÇO, 2019) and that points out the clear relevance in considering the urban analysis to reach a more thorough local energy planning.

In terms of the software chosen for this research, the City Energy Analyst (CEA) presents the potential to become a valuable and user-friendly tool in the decision making processes when dealing with urban and energy planning as well. CEA offers an easily accessible interface with clear display of results gathered from simulations, which is a considerably different feature from the majority of softwares available on the market, and deals with critical variables to the urban context and a more sustainable planning, such as potential for renewable energy and emissions. Additionally, CEA is capable of guiding professionals to a more complete understanding of the impacts caused by the construction industry and help set possible solutions for the problems found during the process through the collected data. Combined with Brazilian urban planning, it is relevant to highlight the potential contributions CEA offers by understanding how it can work within the local challenges, vulnerabilities and strengths. With the growing necessity of decarbonizing our cities, moving towards cleaner and renewable alternatives, this software stands out as an interesting ally for architects, urban planners, policy makers and other related professionals.

1.1 Objectives

This research aims to analyze possibilities the City Energy Analyst can bring to the Brazilian context. CEA is a free and open-source software that analyzes aspects such as energy demand, emissions and renewable energy potential in the urban scale through computer simulations. These characteristics make CEA a potential tool to be used in Urban Energy Planning, when a combination of both urban and energy scenarios take place. For this reason, the hypothesis of this research is that CEA creates positive possibilities for the Brazilian context and, since Brazil is a large and diverse country from an urban standpoint, a new database created with local information could help the results gathered from the simulations to be more precise. As examples of areas to be studied, two Brazilian cities were chosen: Belo Horizonte, capital city of Minas Gerais, and Matozinhos, one of the cities that are part of the Metropolitan Region of Belo Horizonte.

1.1.1 General objective

- To create the first Brazilian database for both 3.34.2 and 3.37.x versions of CEA, suitable for Belo Horizonte, Matozinhos and any other Brazilian city with similar energy and urban scenarios. Through the analysis of multiple documents, feed said database with local information whenever possible and highlight eventual vulnerabilities detected through three different points of view: local regulations, the database and the software itself.

1.1.2 Specific objectives

- To analyze the use of CEA in Brazilian urban and energy contexts through simulations using an original database and the recently created Brazilian one, identifying strengths, current limitations and potential adaptations for it and its database in order to bring them closer to the local reality and to help them answer questions commonly found in other developing nations;
- To highlight the contributions offered by digital tools in urban planning and in local legislations, pinpointing examples of softwares available in the market and using one of them, CEA, in a practical way;
- To discuss about the lack of integration between energy planning and urban planning in Brazil, contributing to the debate of Urban Energy Planning on a local scale;
- To help diffuse the discussion in Brazil and even beyond through a video ín Portuguese with English subtitles especially aimed at urban planners and policy makers, explaining the topic addressed in this research, its relevance to Urban Energy Planning and the role of municipal agents in this process.

1.2 Research motivations and relevance

This section aims to introduce the motivations of each major component that shaped the present research. They will be further addressed in the appropriate chapters.

Table 01: Introduction to the main research motivations

Guiding questions	Answers
Why computer simulations?	● Studies are based on verifiable and quantifiable data; ● Analysis of present and possible future scenarios before taking action; ● Enable fact-based decision making; ● Useful tool to be applied on UEP and to contribute to local legislations.
Why the City Energy Analyst?	● Free with a user-friendly interface, making it more accessible to policy makers and urban planners; ● Analysis of relevant topics, such as energy demand and emissions; ● Focused on UBEM (Urban Building Energy Modelling); ● Analysis of multiple scenarios simultaneously ● Results quite easily turned into graphs.
Why address Urban Energy Planning?	● Current form of urban planning practiced in Brazil is unsustainable; ● Relevant for topics such as energy transitioning and decarbonization; ● Brazil today: disconnection between urban legislations (municipal scale) and energy policies (federal scale).
Why Belo Horizonte and Matozinhos?	● Geographical proximity to each other, allowing relatively similar climate and construction characterization; ● This would also be enable the use of the same database for both places without severely compromising the results; ● Different urban densities to be studied.

Source: Created by the author.

The relevance of the present research is drawn by combining these answers, being initially outlined on a large scale, going to a more local level and then returning to a large scale for broader debates. Urban Energy Planning is a relatively new and still developing field, but its importance is clear when it comes to some urgent topics currently being discussed around the world, such as city decarbonization and energy transitioning. When combining the ongoing and unsustainable forms of urban growth in Brazil - including the unplanned ones, such as “self-construction” - with the disconnection between national energy policies and local urban legislations, the gap between UEP and the practices in the country as a whole becomes even more painfully evident.

Through computer simulations, this research highlights that the contributions of planning urban and energy scenarios simultaneously through quantifiable data can reach public policies and local planning documents in a practical way, being a valuable asset not only for the city’s urban integrity and resilience, but also to the

quality of life of its people and its financial health, since studying present and possible future scenarios can provide forms to predict and deal with eventual obstacles. Through a user-friendly software, the present work showcases an initial path in which policy makers and workers linked to the public administration such as urban planners, architects and engineers can become engaged in this topic collectively, kickstarting the conversation of Urban Energy Planning in their cities, understanding the synergy between urban and energy systems, and transitioning their technical staff into a more practical approach on the matter.

By applying the mentioned topics in two known cities with different complexities and urban realities, this research illustrates the connection between theory and practice, analyzing their real-life situation and drawing conclusions from the results based on quantifiable data available. Last but not least, through the creation of the first Brazilian database for the mentioned software, this research seeks to bring Brazilian professionals closer to the tool by providing a collection of local information to be applied in their analysis and to bring the tool closer to Brazil by analyzing the software and pinpointing the strengths it has to offer, as well as eventual gaps that could be bridged to benefit not only Brazil but other developing nations with similar urban and energy realities around the world.

1.3 Research structure

This research starts with the theoretical approach through a compilation of data from the last 11 years focused on three specific areas within the Brazilian context: energy, CO_2 emissions and renewable energy potential. Since the main target of analysis is a product of the construction industry (the cities), this research often highlights data that address impacts caused by this sector within the mentioned areas and what it represents when sustainable objectives are involved, such as the 17 SDGs (Sustainable Development Goals) described by the 2030 Agenda, created in 2015 by the United Nations.

Subsequently, the research broaches the concept of Urban Energy Planning in the Brazilian context. A characterization of digital tools is also made, more specifically computer simulations, highlighting how they can be applied to an urban planning context. CEA, the chosen software for this research, is presented. The potential for such a tool to be applied in decision making moments during urban planning is

discussed, as well as the limitations found during this research. The cities chosen as case studies, Belo Horizonte and Matozinhos, are addressed and characterized.

The methodology is then presented, structured in three phases: the first being a theoretical and practical approach by getting to know the software documentation and performing test simulations in Belo Horizonte with the original CEA database to understand the software further; followed by a phase where data is collected to create the local database and a third moment, where the research simulations are run using said database and the original one, in order to draw comparisons between them. This research culminates in several comparisons of results collected from the simulations performed with both databases, followed by discussions involving the software and its possibilities, its strengths and limitations found throughout the process taking the Brazilian context into account. Additional developments of this work are detailed and the final considerations regarding the outcomes of the present research conclude this thesis.

2. THEORETICAL FOUNDATION

2.1 Characterization of the Brazilian reality

Aiming at discussing in practical terms the Brazilian reality in regards to its economic sectors and the impacts on the environment, this chapter delves into the national scenarios of energy and CO_2 (carbon dioxide) emissions. The reasons to address these topics are based on some of the relevant areas within the City Energy Analyst, as well as the Brazilian database created for it.

Subsequently to this first theoretical moment, as it is also one of the several variables approached by the CEA, the present work will cast a light on the renewable energy potentials in Brazil, underlining three available options in the country: biogas, solar power and thermal potential for heating.

2.1.1 Electricity and energy matrices

It is known that Brazil's electricity matrix is in its majority composed of renewable energy and it has, in fact, increased in the past 2 years. Data from the 2024 National Energy Report (*Balanço Energético Nacional*, or BEN, in Portuguese), created by EPE (Energy Research Company, or *Empresa de Pesquisa Energética*, also in Portuguese) and based on data from 2023, the renewable and non-renewable alternatives in the electricity matrix were split in 89.2% and 10.8%, respectively. When considering only the SIN (*Sistema Interligado Nacional*, or National Interconnected System, in free translation), which does not include the isolated systems and the self-generation part not injected into the network, this percentage goes up to 93%. This result was a combination of an increase in solar and wind energy production, as well as the continuous participation of hydropower plants (EPE, 2024).

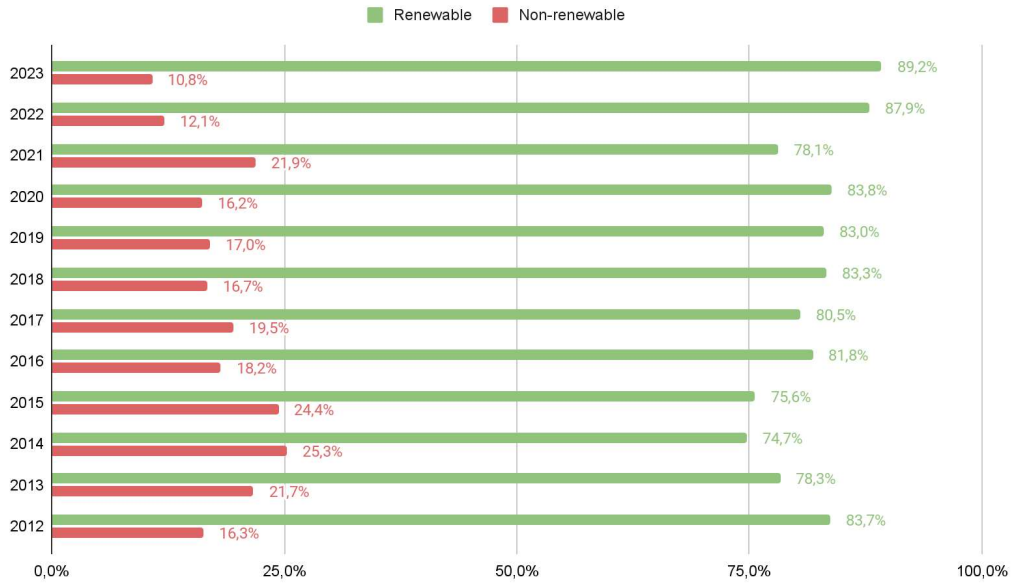
According to the 2024 Electrical Energy Statistical Yearbook (*Anuário Estatístico de Energia Elétrica*, in Portuguese), Brazil was the 2nd country with the highest hydropower installed capacity in the world (110 HW) in 2022, second only to China (414 GW). The total electricity supply in 2023 reached 723.2 TWh (EPE,2024). In the year before, the BEN 2023 (based on 2022 data) pointed out that the renewable and non-renewable alternatives were split in 87.9% and 12.1%, respectively. When considering only the SIN, this percentage increases to 92.1%. In this case, the result was a combination of an increase in hydropower production, which is a prominent energy source in the country, and decrease of use of thermoelectric plants in the

mentioned year (EPE, 2023), which represents an improvement compared to 2021, as data from BEN 2022 showed that the renewable energy share reached 78.1%, while the non-renewable part of the electricity matrix got up to 21.9% (EPE, 2022).

To give a brief context of the thermoelectric plants mentioned previously, there was a decrease of 1.9% of its production in 2023, which shrank its participation in the electricity matrix from 20.4% in 2022 to 19.2% in 2023. As examples of its sources, it is mentioned biomass (reached 39.8% in 2022 and 42.6% in 2023); natural gas (30.3% in 2022 and 28.4% in 2023); coal and derivatives (10.3% in 2022 and 10.4% in 2023); nuclear energy (10.5% in 2022 and 10.7% in 2023) and oil and derivatives (9.1% in 2022 and 7.9% in 2023) (EPE, 2024).

As a compilation, Graph 01 illustrates the internal electricity supply in Brazil in the last 11 years and how both renewable and non-renewable shares developed during this time. A piece of information that is worth remembering is the 2020 coronavirus pandemic and the drought season the country faced in that time, a fact that caused a relevant impact on local hydropower plants. It is possible to notice that, in general, the Brazilian electricity matrix has been keeping a relatively stable balance in the last years. Additionally, its renewable share has clearly been more representative than the non-renewable alternatives.

Graph 01: Internal electricity supply in Brazil in the last 11 years



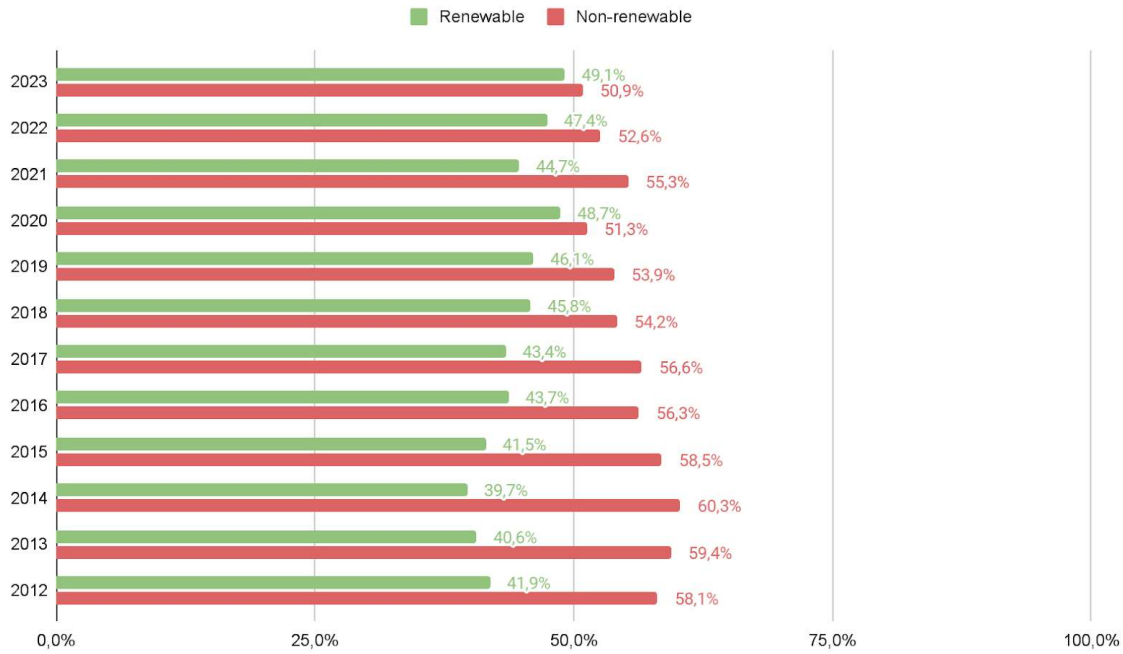
Source: EPE, from 2012 to 2024. Created and compiled by the author.

While the renewable options are mainly represented by hydropower, biomass, solar and wind power, the non-renewable share of the electricity matrix is composed of oil, coal, natural gas, among others. Data from 2020 revealed that the renewable part was responsible for a higher percentage than what was shown in the following year, up to 83.8%, but the decrease in hydropower generation (-8.5%) caused by a drought period forced the use of other electricity options, such as natural gas (+46.2%), which reduced said values. Nonetheless, the increase in solar (+55.9%, 16.8 TWh) and wind power (+26.7%, 72 TWh) assisted in maintaining the percentage at a considerable amount, which is higher than most countries (EPE, 2022).

On the other hand, the energy matrix in Brazil is still predominantly represented by non-renewable resources, reaching 50.9% of its total while the renewable alternatives count for 49.1%, with the former being mainly represented by oil and the latter by sugarcane biomass (EPE, 2024). In the year prior, the 2023 National Energy Report pointed to the non-renewable share of the energy matrix reaching 52.6% while the renewable alternatives count for 47.4% (EPE, 2023). These results show, once again, an improvement compared to 2022, in which the non-renewable share of the energy matrix reached 55.3% while the renewable part represented 44.7% (EPE, 2022). As mentioned, the growth in hydropower generation was a pivotal fact for such a positive outcome (EPE, 2023). In 2023, the total energy generation in the country reached 313.9 Mtep (millions of tons of oil equivalent, in Portuguese), which represents an increase of 3.5% compared to 2022. In regards to electricity generation, the report has shown a growth of 33.2 TWh in 2023, which accounts for a rise of 4.8% compared to the previous year (EPE, 2024).

Similar to the previous graph, Graph 02 compiles data from the last 11 years, but now focusing on the energy matrix and how the renewable and non-renewable shares developed in this period. The national energy matrix has been prominently non-renewable in the studied period, but the numbers are not as distant as the ones of the electricity matrix. This highlights the potential the country possesses in also pivoting said matrix into a mainly renewable one in the coming years.

Graph 02: Internal energy supply in Brazil in the last 11 years



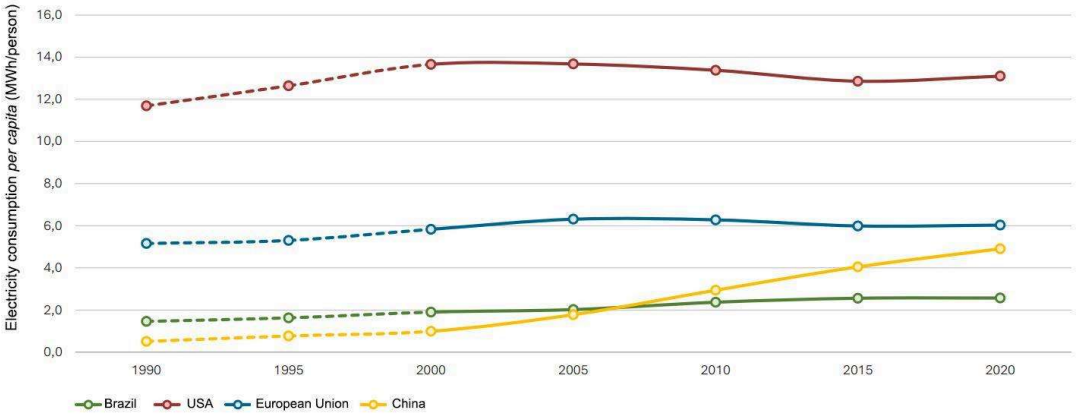
Source: EPE, 2023 (BEN Interativo). Created and compiled by the author.

For comparison purposes, the 2021 report (based on data collected in 2020) revealed that the national energy matrix was composed of 48.4% of renewable alternatives and 51.6% of non-renewable sources (EPE, 2021). The 2020 report, with data gathered in 2019, indicated percentages of 46.1% and 53.9%, respectively (EPE, 2020). According to the 2021 National Energy Report, the impact of the COVID-19 pandemic (especially in its early months) in the residential and commercial sectors was caused by a combination of the social distancing measures and the closing of commercial establishments. The commercial and services sector was one of the most affected during this time in Brazil, while the residential sector presented a spike in the electricity consumption compared to 2019: the electricity consumption of the former decreased 10.5% and the latter increased 4% (EPE, 2021).

Although the majority of the world has reduced its energy consumption in recent years, Brazil and some other countries have been going in the opposite direction since 2013, according to data from IEA (International Energy Agency). Specialists in this field state that there is still no consensus over the reason for such differences compared to other nations, but faults during planning are considered to be one of the probable causes (NOGUEIRA, 2017). Image 01 illustrates data related to electricity consumption *per capita* involving Brazil (in green), China (yellow), the United States

(maroon) and the European Union (blue). The Y-axis represents the consumption values, while the X-axis indicates the analyzed years. It is possible to notice that China and Brazil have reached an increase in consumption, with the former rising up more drastically in 2020 than the latter. Among the four economies considered, Brazil has the lowest growth in consumption *per capita* and the USA, the highest.

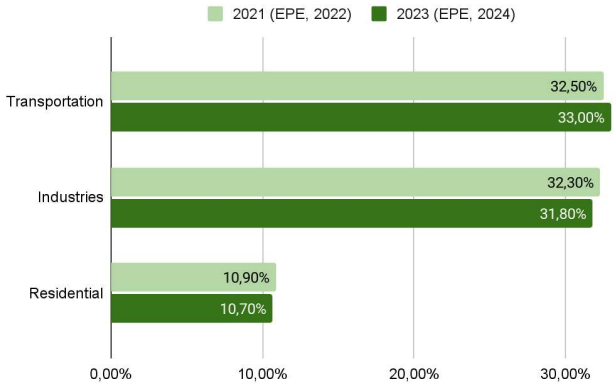
Image 01: Electricity consumption *per capita* (MWh/person) - Brazil x World



Source: EPE, 2024.

In 2021, the energy consumption expanded 3.5%, which speaks for 262.1 Mtep, compared to 2020 and the sectors with the highest rates were transportation, industries and residential buildings (EPE, 2022). The energy consumption in 2023 reached 282.5 Mtep (4% higher than 2022), with the main sectors, once again, being the ones mentioned (EPE, 2024). Graph 03 illustrates a brief comparison between the values reached by each of these sectors in the aforementioned timeframe.

Graph 03: Comparison of the most prominent sectors in energy consumption (2021 and 2023)



Source: EPE (2022); EPE (2024). Created and compiled by the author.

The industrial and transportation sectors heavily employed more non-renewable resources in their activities: the former, 11.8% more of coal and 20.8% more of natural gas; the latter, 32.8% more of kerosene, 9.8% of gasoline and 9.1% of diesel. Despite displaying an increase of 6.5% in the use of biodiesel, renewable energy alternatives accounted for only 23% in the transportation sector's matrix, a reduction of 2% compared to 2020 (EPE, 2022).

Data linked to the electricity final consumption rates in the country in 2021 indicated an escalation of 4.2%, with the main sectors responsible for it being the industries (+7.5%, 15 TWh), followed by the commercial sector (+5.7%, 4.8 TWh), the agricultural sector (+4.2%, 1.4 TWh) and the residential one (+1.1%, 1.6 TWh) (EPE, 2022). In 2022, the commercial sector showed an increase of 6.8 TWh (+7.5%), the residential electricity consumption grew 3.4 TWh (+3%) and the public sector had an increment of 1.9 TWh (+4.3%) (EPE, 2023).

Regarding specifically the residential sector, the energy matrix is in its majority renewable (70.7%), since most of it is represented by electricity, which is mostly supported by hydropower plants (EPE, 2023). The main electricity suppliers for households in the country are the power companies, that represent 99.48%, followed by electricity produced on-site, with 0.12% (ELETROBRAS, 202-). The residential energy consumption was split among electricity (46.2%), which is the main power source for artificial lighting, cooling and home appliances in general; followed by firewood (25.9%). The latter is an energy source that has been consistently replaced in the last years in Brazil, but had an expressive uptick in 2022 (EPE, 2023) due to the price increase of LPG (Liquefied Petroleum Gas), mainly used by the residential sector for cooking purposes.

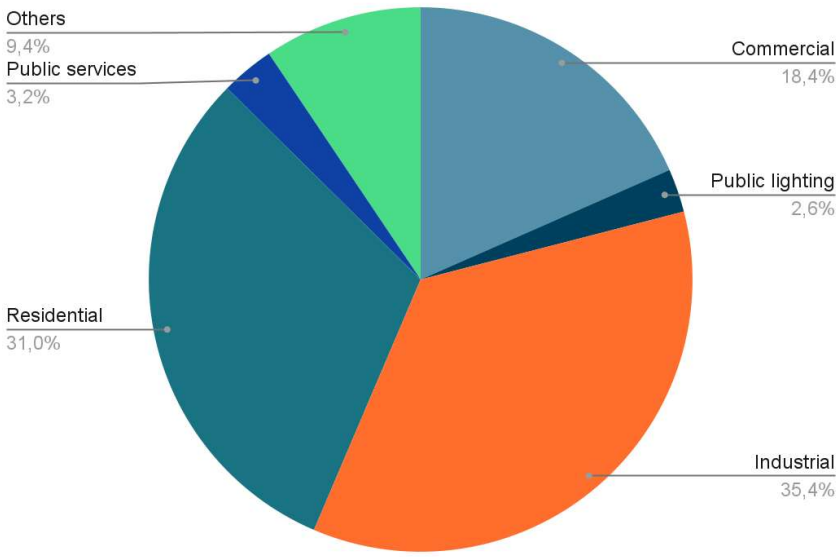
In broader terms, buildings are responsible for almost 90% of the national LPG consumption and 40% when it comes to firewood (EPE, 2020). These particular scenarios illustrate a socioeconomic vulnerability, where part of the Brazilian population struggled to purchase such fuel sources, having to resort to different alternatives while prices were fluctuating - something very different from Swiss social reality. According to EPE (2023), the LPG itself represented 21% of the energy consumption in the residential sector in 2022 and natural gas accounted for 1.6%. Natural gas has been able to replace both firewood and LPG as there is an expansion of its distribution grid nationwide (EPE, 2024). Solar thermal energy - used for water heating in open collectors, closed collectors and evacuated tubes - has

grown in the last few years and reached 12.484 GWh in 2023, in which the residential sector represented 79.7% of its consumption, followed by the commercial sector with 17.3% and the industry, with less than 3% (EPE, 2024).

According to a 2023 research conducted by ANEEL (National Agency of Electrical Energy, in literal translation), Brazil's centralized installed capacity in the electricity matrix has surpassed 190 GW (gigawatts), provided by 23,400 generating units across the country. This number is composed of large scale hydropower plants (53.58% or 103.2 GW), thermal power stations (24.7% or 46.15 GW), and wind turbines (13.12% or 24.92 GW). Among all states, three of them stand out in regards to their production growth in the first two months of the year: Rio Grande do Norte (579.6 MW), Minas Gerais (494.0 MW) and Bahia (347.9 MW).

Delving into more details in terms of the electricity consumption in a Brazilian context, data from the 2024 Electrical Energy Statistical Yearbook illustrates that the residential (164.735 GWh), commercial (97.913 GWh) and public services sectors (16.921 GWh) represent 52.56% (279.569 GWh) of the total electricity consumption registered per class in 2023 (531.873 GWh). The industrial sector alone was responsible for 188.507 GWh (EPE, 2024). Graph 04 illustrates the shares of each of the mentioned sectors in percentage.

Graph 04: Most prominent sectors in electricity consumption in Brazil (2023)



Source: EPE (2024). Created and adapted by the author.

These numbers track with another relevant document: according to the 2050 National Energy Plan (*Plano Nacional de Energia* 2050, in Portuguese), the buildings sector in

Brazil represent close to ⅙ of the energy consumption and 50% of the electricity consumption in the country (EPE, 2020). It highlights the visible potential that the building sector possesses in the improvement of energy efficiency within the next few years, a crucial goal set in the National Energy Plan 2050.

Furthermore, it is also possible to analyze numbers that specifically refer to the use of appliances in buildings. According to a survey conducted in 2019 by ELETROBRAS (202-), a major Brazilian power utility company and called “Possessions and Habits Research” (*Pesquisa de Posses e Hábitos*, in Portuguese), the most common electric appliances in households in Brazil were freezers (33.73%), refrigerators (24.10%) and blenders (19.88%) (ELETROBRAS, 202-).

The same survey showed that 83.31% of Brazilian households did not possess any air-conditioning equipment while 16.69% did. On the other hand, 75.95% of residences had at least one fan or air circulator, while 24.05% did not. In those where air conditioners were present, 58.33% were traditional split systems and 30.08% were window air conditioners. Around 85.2% of households admitted using air-conditioning systems six to seven times a week, with the months with the highest demands being December, January and February (summer in the Southern hemisphere) and the peak times being 8 p.m. to 6 a.m. (ELETROBRAS, 202-).

When it comes to the lighting systems, the peak times were detected as being 6 p.m to 10 p.m and the most prominent type of lamps found in the surveyed households were fluorescent and LED lamps, the latter generally being more energy efficient. In terms of water heating, 40.9% of the surveyed households declared having showers and/or taps with water heated by electricity, while 56.99% declared not having a hot water supply whatsoever (ELETROBRAS, 202-).

Commonly used in Brazil due to its affordable price and less complex installation, an electric shower is an equipment that is connected to a cold-water pipe and heats the liquid instantly through a metallic heating element that is powered by electricity. According to ELETROBRAS (202-), 37.52% of showers had the water heated by electricity and 60.23% did not offer hot water at all. The peak times for showers to be used were from 6 to 7 a.m, a common period of time for working people to prepare for the day and leave home, and from 6 p.m to 9 p.m. The months in which electric showers were set to work in the highest temperatures were June, July and August (ELETROBRAS, 202-), which coincides with winter in the Southern hemisphere. Last but not least, another example of home appliances that represent a considerable

portion of electricity consumption and is present in the majority of Brazilian households is the refrigerator, being used six to seven times a week in 97.07% of the surveyed buildings (ELETROBRAS, 202-).

TAVARES (2016) states that, within the construction sector, the energy consumed during the building use and maintenance phase is the main pollution generator. Additionally, the amount of energy used by water heating, air-conditioning and artificial lighting systems in a household, for instance, surpasses the energy quantity spent on the extraction of raw materials and its manufacturing. Data from the 2024 National Energy Report illustrate that the Brazilian buildings sector is cleaner than others, such as the transportation and industry ones, when it comes to the matrix renewability and emissions (EPE, 2024).

In order to complement the information previously addressed and for comparison purposes, additional data is displayed in the following table to further understand the habits of the population in terms of electric equipment and home appliances, as well as their use patterns and building characteristics. However, not only information regarding the country is addressed, but also from a specific Brazilian state where the two studied cities of the present research are located: Minas Gerais. The aim with this strategy is to comprehend the nuances in behavior on different scales. The same survey mentioned beforehand also covered topics such as the residents characteristics, the construction attributes of residential buildings, use habits, among others. Table 02 illustrates a compilation of some data disclosed in said report, focusing on both state and national scales. It is worth highlighting that, although there were several examples of home appliances shown in the report, the following table presents data about water heating and air-conditioning systems due to their relevance in the energy consumption rates.

Table 02: Main characteristics of the residential sector in Brazil and Minas Gerais - Possessions and habits (July, 2018 to April, 2019)

	Brazil	State of Minas Gerais
Residents	● Habitants per household: On average, 3 people; ● Predominant age range: 18-65 years old (63.95%) and below 10 (16.29%).	● Habitants per household: On average, 3 people; ● Predominant age range: 18-65 years old (66%) and below 10 (13.5%).
Buildings	● The majority of the people lived in houses (95.86%), followed by those who lived in apartments (4.05%); ● 98.77% would be exclusively residential buildings; 0.89% would have mixed use; ● Predominant external colors would fall into the lighter (70.61%) and medium categories (25.87%); ● Surveyed households would have windows facing mainly north (34%), east (19.6%) and northeast (11.4%); ● Around 58% of households offered no shading element in their windows. The ones which offered any would have balconies over the openings (16.87%); ● External walls: brickwork with external coating (82.83%), followed by the same option with no coating (9%); ● Main roof systems: clay tiles (37.10%) and concrete slabs (26.72%).	● The majority stated to live in houses (97.64%), followed by those who lived in apartments (2.36%); ● 98.45% exclusively residential; 1.46% with mixed use; ● Lighter external colors would dominate the survey (58%), followed by medium shades (39%); ● Windows would be facing mainly north (25.27%), northeast (24.82%) and east (18.45%); ● Around 70% of the households with no shading element; 17.73% with balconies over the openings (17.73%); ● Predominant composition of external walls: brickwork with external coating (72%), followed by the same option without coating (19.73%); ● Prominent roof systems: concrete slabs (60.91%) and clay tiles (24%).
Energy sources	● Power distribution company (99.48%); ● On-site generation (0,12%).	● Power distribution company (99.73%); ● On-site generation (0,09%).
Habits	**WATER HEATING** - <u>Shower - Main energy sources for heating</u>: Electricity (37.52%), solar (0.96%) and gas (0.59%). Showers without water heating represented 60.26%; - 24.31% of the support systems for water heating through solar energy used electricity; - Around 34% of the final users who possessed solar panels attested cleaning them regularly; - Almost 39% of the population knew about water heating systems using gas and over 52% attested knowing solar heating systems; - Showers: used, on average, 3.95 times a day; - Average duration taking showers:	**WATER HEATING** - <u>Shower - Main energy sources for heating</u>: Electricity (60.39%), solar (3.35%) and gas (0.27%). Showers without heating would represent 35.32%; - Almost 54% of the support systems for water heating through solar energy used electricity; - Almost 54% of the solar panel users stated cleaning them frequently; - More than 57% of the users knew about water heating systems using gas and more than 78% attested knowing solar heating systems; - Showers: used on average 4.17 times a day; - Average duration taking showers:

		6 to 10 minutes (45.59%); - Around 24% of the surveyed users declared they would use a solar powered water heating system.		6 to 10 minutes (51.28%); - Over 47% of the surveyed people declared they would use a solar powered water heating system.
	AIR-CONDITIONING SYSTEMS	- Around 83% of households did not possess air-conditioning systems in place. Almost 17% did. - Predominant types: Split (58.33%) and window AC (30.08%); - 80.73% are used in the "Cold" position; - 49.54% of the users declared not unplugging them from the power outlet while they are not being used; - Predominant use time: midnight - 6 a.m. and 7 p.m.- 11 p.m.; - AC systems are more used from December to February, during Brazilian summer; - Most used temperatures: 22 °C; - 88% of the users affirmed that they cleaned the filters regularly; - Throughout the year, the average frequency of use is defined as "intense", which translates to 6 to 7 times a week.	**AIR-CONDITIONING SYSTEMS**	- 95.51% of households did not have any air-conditioning system in place. About 4% did. - Predominant types: Split (81.63%), followed by window AC (14.29%); - Almost 92% are set in the "Cold" position; - 55% do not unplug the equipment from the power outlet while they are not being used; - Predominant use time: midnight - 6 a.m. and 7 p.m.- 11 p.m.; - AC systems are more used from December to February, during Brazilian summer; - Most used temperatures by users: 23 to 24 °C; - Almost 92% of the users affirmed cleaning the filters regularly; - Similar to the national scenario, the frequency of use is "intense" (6 to 7 times a week) throughout the whole year.

Source: ELETROBRÁS, 2019; ELETROBRÁS, 202- (compiled by the author).

The previous table points out that both scenarios are similar in several aspects, predominantly showing differences in the values reached. Two noticeable areas that displayed some divergences were the predominant orientations of windows and the most representative roof types. Some numbers are clearly relevant in both scales, such as the predominant presence of exclusively residential buildings surveyed; the dominance of masonry walls in said constructions and the main origin of the energy used in the surveyed households. When talking about the use patterns, the predominance of electric showers also does not come as a surprise, as it is the most adopted equipment for such use in the country. The frequency of showers during the week and the high use of air-conditioning systems throughout the year are traits explained by, among other reasons, the dominant hot climate commonly found in Minas Gerais and Brazil in general.

A positive trait to be mentioned is the prevailing lighter colors found in the external walls of the surveyed buildings, which is directly linked to the amount of heat load by

the façades. Although it is not the only variable to analyze, lighter colors do impact positively in the internal thermal comfort and, consequently, the energy consumption linked to cooling systems. Another characteristic that has an effect on these two topics is the windows orientation: in the Southern Hemisphere, windows pointed towards west, north and northwest, for instance, receive a high amount of solar radiation in the most critical periods of the day (around 3 p.m.), while east-facing façades tend to receive lower heat loads, predominant during the morning. This, in combination with the lack of sun shading devices in the majority of the surveyed buildings, may have impacted the energy consumption linked to cooling systems during the warmer months of the year in both state and country scales.

2.1.2 Renewable energy alternatives

As mentioned previously, the electricity matrix in the country is mostly composed of renewable alternatives, such as hydropower, biomass, solar and wind power, among others (EPE, 2022; EPE, 2024). In this section, three sources will be addressed with additional details: Biogas, solar power and thermal potential for heating.

Biogas

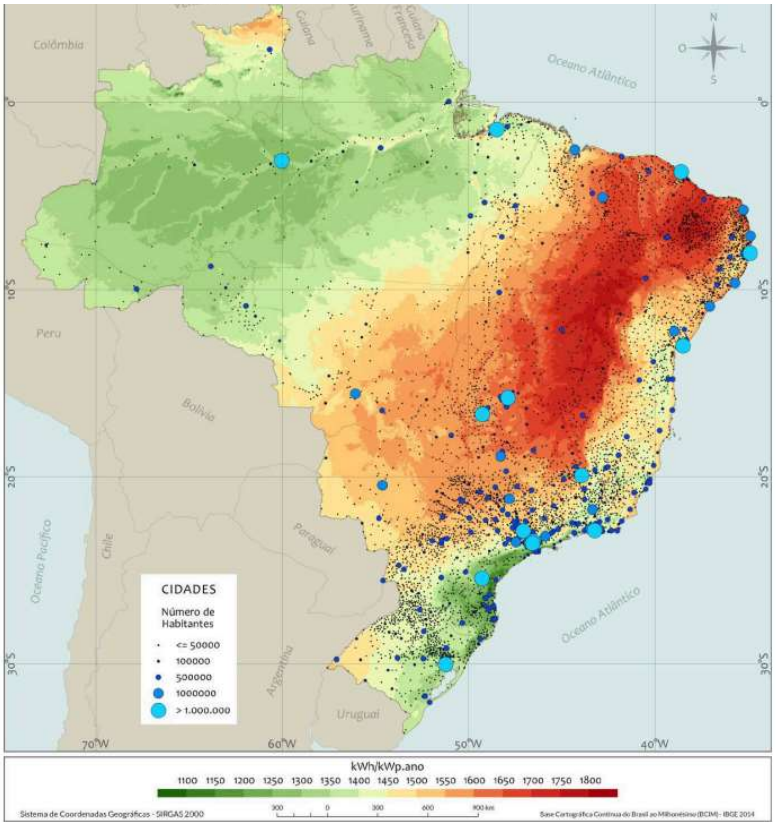
Biogas is an environmentally-responsible energy source and renewable biofuel produced by bacteria that decompose organic matter and other types of waste. Brazilian biogas installed capacity is heavily condensed in areas with higher potential of organic matter production, as well as waste originated from agriculture, cities, industries and forests. Among the states with higher installed capacity in Brazil, it is worth mentioning São Paulo, Minas Gerais, Bahia and Pernambuco (EPE, 2022).

According to data gathered from ANEEL in 2023, Brazil has 484 active biogas power plants that produce a total of 350,469.46 kW of electricity. This value is split between distributed generation (installed capacity of 104,771.66 kW) and centralized generation (granted power of 245,697.8 kW). In order to clarify, “distributed generation” refers to the electricity produced at the consumption units or near them; while “centralized generation” indicates the energy produced by large generation facilities. Brazil’s highest biogas producers, regarding distributed generation, are Minas Gerais, Paraná and Santa Catarina. In relation to centralized generation, the states that stand out the most are São Paulo, Paraná and, once again, Minas Gerais (ENERGIA E BIOGÁS, 2018-2023).

Solar power

Brazil has a well-known potential for solar power, as illustrated on Image 02, both for energy and heating generation.

Image 02: Solar power potential - Annual energy production



Source: PEREIRA *et al.*, 2017. Adapted by the author.

For comparison purposes, it is possible to generate more electricity in the region with the lowest direct solar irradiance rates in Brazil than in the sunniest area in Germany. The regions with the highest global irradiance incidence in Brazil are the Northeast, followed by the Midwest and Southeast portions, and lastly the north region of the country (PEREIRA *et al.*, 2017).

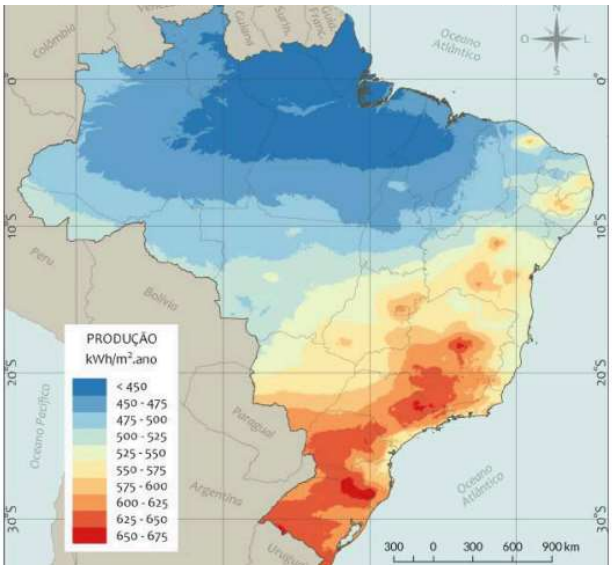
The mentioned image shows the photovoltaic generation potential throughout the entire territory, in which it is possible to notice that the center and northeast areas are the ones with the highest rates. The map includes not only large-scale power plants, but also the photovoltaic units installed on building roofs, for instance. The blue dots scattered across the land represent the population concentration in each area. The combination of the country's relevant generation potential with the price reductions that photovoltaic systems have suffered during recent years are important factors to encourage the use of solar power to produce energy (PEREIRA *et al.*, 2017).

Thermal potential for heating

The use of solar energy to water heating in temperatures below 100 °C (212 °F) is currently the most widespread application in Brazil, especially to replace electrical and gas heating systems, commonly used in showers, for example. Some of the reasons that make this possibility so attractive in Brazil are the simplicity and vast availability of the technology used to transform solar power into thermal energy, as well as the tax breaks offered in some situations (PEREIRA *et al.*, 2017).

PEREIRA *et al.* (2017) stated in the time of their research that, in the residential sector alone, the energy used for water heating tended to represent around 24% of the total amount of electricity consumed during the years and that one of the main actors responsible for such expressive rates are showers. From an economic standpoint, the feasibility of water heating through solar power in Brazil is strongly linked to the higher costs that the traditional heating system presents. It is also relevant to mention that Brazil has considerable possibilities to expand its installed capacity, further than other nations with less sunlight (PEREIRA *et al.*, 2017).

Image 03: Thermal energy annual generation per solar panel area. Reference system: daily consumption = 300 L; water tank x solar panel ratio = 75 L/sq m; temperature = 40°C).



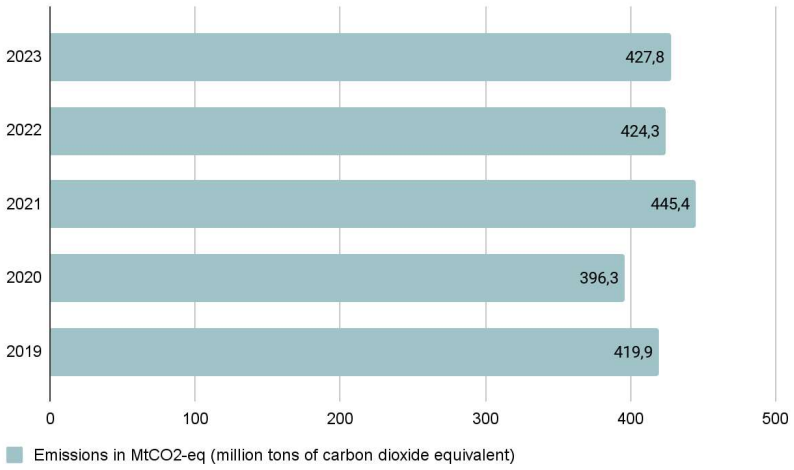
Source: PEREIRA *et al.*, 2017.

2.1.3 CO_2 Emissions

This section will deal primarily with data regarding operational carbon footprint, mentioning embodied carbon only in specific cases when related information is displayed.

In reference to operational CO_2 (carbon dioxide) emissions, Graph 05 illustrates the values reached by the Brazilian energy matrix from 2019 to 2023, with numbers in $MtCO_2$-eq (million tons of carbon dioxide equivalent, in Portuguese).The results illustrate that there have been fluctuations in the past 5 years, one of them being the impacts that both the pandemic and the decrease in the hydropower energy supply had on the fluctuation between 2019 and 2020. From the 427.8 $MtCO_2$-eq emitted in 2023, the transportation sector was responsible for 217 $MtCO_2$-eq, followed by the industrial sector (73.9 $MtCO_2$-eq) and the residential one (18.4 $MtCO_2$-eq). Other industries accounted for 118.4 $MtCO_2$-eq in total (EPE, 2024).

Graph 05: Operational CO2 emissions by the Brazilian energy matrix (2019-2023)

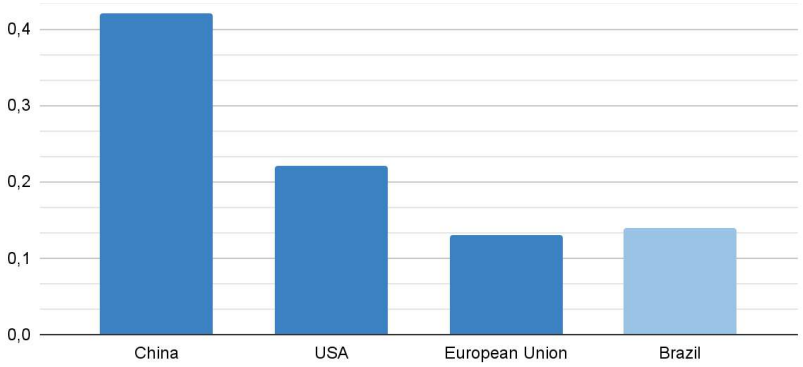


Sources: EPE (2020); EPE (2021); EPE (2022); EPE (2023); EPE (2024). Created by the author.

When it comes to CO_2 emissions *per capita*, the most recent report has indicated that in 2022 and 2023 the values reached 1.97 tCO_2-eq/person. With the average annual growth rate, such values are expected to go up to 2.30 tCO_2-eq/person in 2030. It is important to highlight that Brazil's current emissions *per capita* rates are substantially lower than other countries and group of nations, such as the United States (13.8 tCO_2-eq/person in 2021), China (7.5 tCO_2-eq/person in 2021) and the European Union (5.6 tCO_2-eq/person in 2021) (EPE, 2024). When discussing the carbon intensity in the country's economy, measured in $kgCO_2$/US$ppp, the contrast

diminishes but it is still present (Graph 06): with the aid of an analogy, to produce one unit of a product, the Brazilian economy emits, during the manufacturing process and energy consumption, the equivalent of 34% of what the Chinese economy releases, 66% of the American and almost the same as the European economy (EPE, 2024).

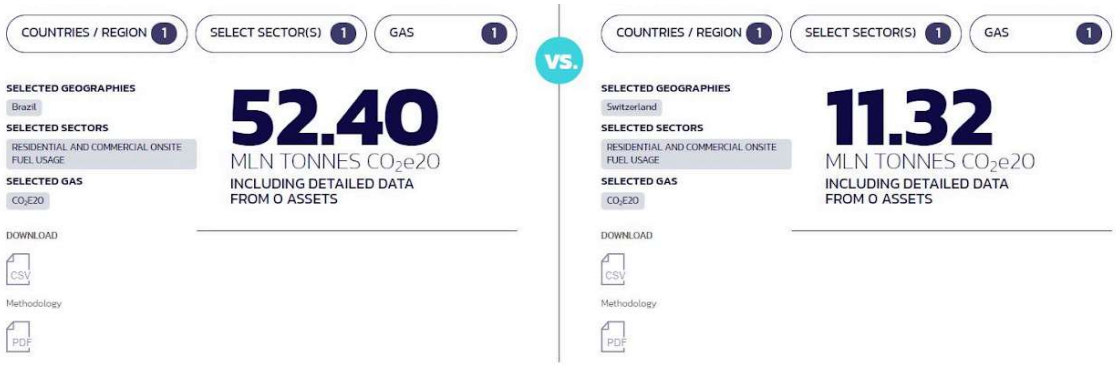
Graph 06: Carbon intensity in four countries/group of nations in 2021



Source: EPE, 2024 (created by the author).

For comparison purposes and taking the context of the present research into account, Image 04 shows data collected from the Climate Trace website where Brazil and Switzerland are compared within a span of 20 years in terms of CO_2 emissions and other greenhouse gases. The chosen sectors were the residential and commercial ones, focusing on their on-site fuel usage. Naturally, it is important to visualize their results bearing in mind the differences between their sizes, energy matrices, economic sectors and consumption patterns.

Image 04: Emissions in CO_2e20 (Carbon Dioxide Equivalent on a 20-year horizon)

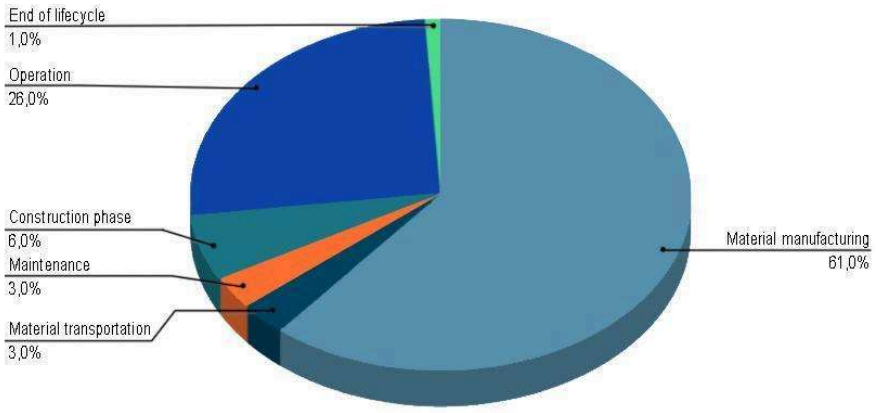


Source: CLIMATE TRACE, 202-.

Alongside the impacts on energy consumption, the construction industry is one of the most prominent responsible sectors in regards to CO_2 emissions worldwide, releasing 38% of the total amount gathered according to a report published by the United

Nations Environment Programme in 2019. It is considered the highest level in recent years and this increase represents 9.95 gigatonnes in the mentioned year (United Nations, 2020). In Brazil, this sector has representative numbers proving its influence on emissions, from the raw material extraction and manufacturing up to the end of the building's life cycle and an eventual retrofit or demolition. Graph 07, which displays data released during a lecture at ENTAC (National Technology Conference of the Built Environment, in free translation) in 2022 conveys that the overwhelming majority of CO_2 emissions in the context of Brazilian social housing, for instance, lies on the material manufacturing processes (embodied carbon footprint), followed by the operation phase (operational carbon footprint). The former indicates that, in this scenario, the embodied carbon rates are far superior than the operational ones.

Graph 07: CO_2 emissions in social housing in Brazil.



Source: BESSA, S. A. L., 2022 (Created by the author).

On a local scale, Belo Horizonte City Council released in 2023 a report with data regarding the emissions of greenhouse gases in the city from 2009 to 2021. The main goal was to establish a local emission profile and create mitigation strategies. The document compiles information of many economic sectors, including the residential, commercial and institutional shares. Table 03 deals with the operational carbon footprint, summarizing the stationary energy sources in each sector that contribute to anthropic emissions. Scope 1 considers emissions from fossil fuel burn in residential buildings, commercial locations and industries; while Scope 2 includes emissions linked to the entirety of the electricity demand (PBH, 2023).

Table 03: Economic subsectors, their scopes and main stationary energy sources.

Subsector	Main stationary energy sources		
	Scope 1		Scope 2
Residential	LPG (Liquefied Petroleum Gas)		Electricity (Brazil)
	Natural gas		
Commercial/ institutional	Diesel (Brazil)	LPG	Electricity (Brazil)
	Natural gas	Fuel oil	

Source: PBH, 2023. Created by the author.

In terms of operational carbon, from 2011 to 2014, there was a rapid growth in emissions in the city. Brazil hosted the FIFA Men's World Cup in 2014, when the emissions reached a peak, and Belo Horizonte was one of the chosen cities. From 2014 to 2016, there was a fluctuation with no clear signs of future increase or decrease tendencies. However, when considering data from 2014 to 2020, a considerable decrease of 63% in emissions regarding electricity is noticed. In 2020 and 2021, a period when the coronavirus pandemic was ongoing, increases of 195% in emissions linked to diesel and 100% linked to electricity were noted. Nonetheless, there was a decrease in total emissions of around 14% in the same period, probably also due to the sanitary crisis and its social-economic impacts. The document highlights a correlation between emissions and GDP fluctuation (PBH, 2023).

Regarding the economic sectors mentioned, the residential one presented fluctuations between 2009 and 2012, showing an increase in 2013 and 2014, decreasing from 2014 to 2018, going up again in 2019 and down in 2020, ending 2021 with a massive increase - for comparison purposes, emissions of 295.286 tCO_2e in 2020 to 393.101 tCO_2e in 2021. The latter may have happened due to the pandemic and the sanitary measures put in place, such as the need to work from home. The commercial/institutional sectors also showed a similar pattern, with different values. In the same logic, there was a decrease of emissions from 2019 to 2020 linked to the social and economic restrictions related to the coronavirus pandemic, followed by an increase in 2021.

2.2 Urban Energy Planning

This section of Chapter 2 aims to build a context to address the topic of Urban Energy Planning, a field of study that is crucial to the present research since its focus involves both the urban fabric and the energy it demands due to its characteristics. By building a line of reasoning that mentions recent key facts involving energy demand, urban growth and the relationship between man and the environment, this section highlights the importance and intrinsic connection between the energy and urban systems, as well as how paramount it is to consider them simultaneously during planning phases.

The climate and energy crisis have been causing negative impacts all around the world, even more so to developing countries, according to the United Nations. These economies need to address both the constant increase in the energy demand and the imbalance of distribution of this resource due to local economic disparity. The impacts of such a crisis in these countries are even more intense, bringing issues such as food insecurity, one of the challenges tackled by the UN 2030 Agenda. But despite having lower goals in terms of emissions and demand reduction when compared to financially-gifted countries, developing nations still need to address the current challenges imposed by the climate crisis (UN HABITAT & ICLEI, 2009). The balance between reducing impacts without worsening already existing local problems in its territory is a delicate feat. However, a relevant fact to mention is that the current situation is also an important moment to shed a light on the opportunities and difficulties that each local context offers (UN HABITAT & ICLEI, 2009).

Speaking of the climate crisis, there have been reports done in the last few years focused on understanding the human negative impacts on Earth's ecosystem and climate behavior, as well as trying to predict possible future scenarios with the available data to serve as an aid to come up with strategies to mitigate such drawbacks in time. The 2014 Synthesis Report on Climate Change, created by IPCC (Intergovernmental Panel on Climate Change), has brought relevant information about the impacts the energy sector and human emissions have on the planet. According to said document, also known as AR5 (Assessment Report 5), the continuous greenhouse gas emissions will cause severe warming and long-lasting negative consequences in Earth's climate, ecosystems and people's well being, causing frequent droughts, floods, heat stress, water and food scarcity, etc..

Current human activities affecting emission represent such a huge amount of the anthropogenic CO_2 emissions that it is estimated that about half of the cumulative values occurring between 1750 and 2011 were concentrated in the last 40 years alone. Furthermore, as economic sectors, electricity and heat production represented 25% of direct greenhouse gas emissions globally and buildings reached 6.4%. Within the mentioned 25%, buildings were responsible for 12% of direct CO_2 emissions and the energy sector, 1.4% (IPCC, 2014).

AR5 (IPCC, 2014) also mentions that the total annual anthropogenic greenhouse gas emissions have increased substantially between 2000 and 2010, having as the main actors the energy sector (47%), industry (30%), transportation (11%) and building (3%), which corroborates with data previously presented in this research. When dealing with indirect emissions, the contributions by the building and industry sectors rise. Population growth and cities urbanization, as well as the economic activities, lifestyle, energy use and land use patterns are among the main drivers of GHG (greenhouse gases) emissions. It is said that the increase in the use of coal in the years analyzed by the AR5 have slowed and reversed the trend of gradual decarbonization (IPCC, 2014).

The AR6, the following report created in 2023, also used similar ways to display the research findings and predict possible scenarios. Furthermore, it makes direct connections to the previous document. As a brief example, AR6 mentions that an increase of the planet's surface temperature was detected since AR5 and, although it did not represent an additional warming since the last report, it was probably motivated by a progressive warming since 2003-2012. AR6 also informed that the human influence on the climate crisis has strengthened since AR5 (IPCC, 2023).

From a promising point of view, mitigation policies have been put in place, as well as international agreements and an increase of public awareness of the matter since AR5. These strategies have helped accelerate the efforts to globally address the climate crisis and the need to act collectively at several levels of governance. Additionally, they have also contributed to a decrease of global energy and carbon intensity. Low-energy technologies have become more affordable in some countries as time progresses and options to achieve zero emissions in the energy sector, buildings, transportation and industries are now available. The unit costs of specific forms of renewable energy have considerably decreased and the installed capacity of renewable energy in some territories have significantly gone up. Some adaptation

planning strategies have created benefits, presenting a real potential of reducing climate risks going towards a more sustainable development (IPCC, 2023).

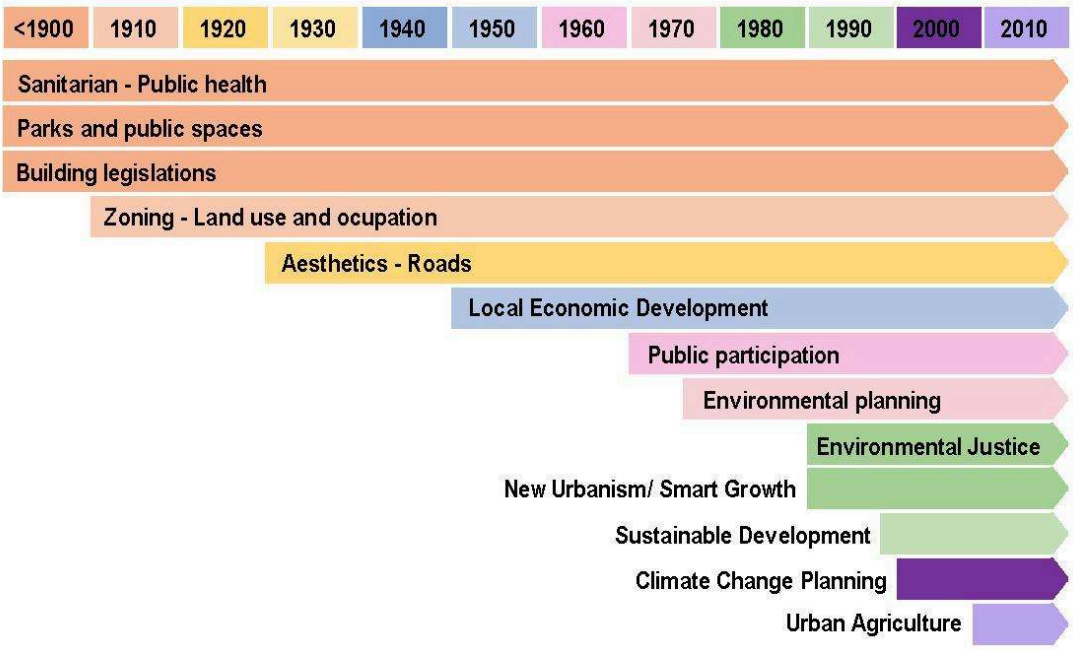
In the last years, urban areas have been through and intense and, in developing countries, relatively often unplanned growth. The urbanization rates and social contexts of developing countries are strikingly different from richer nations (UN HABITAT & ICLEI, 2009). In Brazil, for instance, the urbanization process is expected to grow and, as a consequence, so is the use of resources (MARINS & ROMÉRO, 2012). The rise in population in the cities has been expressive and specialists predict this situation will continue for the foreseeable future until the majority of the world's population is concentrated in urban areas (UN HABITAT & ICLEI, 2009). Urban areas can be considered as physical, functional and energy systems with several codependency relations among them (MARINS & ROMÉRO, 2012). Buildings have interactions with several systems in an urban environment, such as the climate, transportation patterns and energy demand/ end use (HONG *et al.*, 2020).

Bearing these observations in mind, it is clear the importance that cities have and will continue to have in terms of energy management, greenhouse gas emissions and the climate crisis. The increased urban growth has brought negative consequences, such as the rise in the energy demand, the exorbitant consumption of natural resources and the lack of adequate services the cities have to offer their residents. According to the United Nations, redirecting the efforts towards a carbon-neutral, more efficient economy is imperative. As some of the advantages of a sustainable urban planning, it is worth mentioning the improvement in the air quality, better use of financial resources, increase in new job offerings, local economic development, possibilities of partnerships between the public and private sectors, among others. From an economic standpoint, working to minimize or extinguish the impacts of the climate crisis will be considerably less expensive than having to live with its damages permanently (UN HABITAT & ICLEI, 2009).

Evolving the way cities are planned is imperative not only to maintain a healthy growth for the current generation but also for the future ones. Urbanism has developed new strategies to tackle problems throughout the years to answer the needs of its time and now it faces the necessity to do the same once again. Image 05 (COLLAÇO, 2019) illustrates the development of urbanism in the past century. It is noticeable the appearance of forms of planning linked to environmental and urban aspects from the 1970s on, culminating in strategies that involved the consequences

of the climate crisis. Some reasons for this tendency are the Oil Crisis and several global meetings that took place to collectively sort common goals towards a more sustainable and efficient development.

Image 05: Evolution in Urban Planning priorities in Europe and North America



Source: WHEELER (2013) *apud* COLLAÇO (2019). Adapted by the author.

According to COLLAÇO (2019), the term Urban Energy Planning (also known as UEP) refers to the harmonic unity between Energy Planning and Urban Planning, involving both their potential and challenges. It is a relevant way to address current problems and opportunities of improvement in the urban scale when it comes to sustainability and energy efficiency. The first mention of this term is known to have been done in 1978, after the 1970s Oil Crisis, but the topic still has relatively few examples in the literature nowadays (COLLAÇO, 2019). Fortunately, there is an increased interest in this subject. Some of the foremost paradigms of a national energy planning are energy security, the expansion of generation capacity through lower costs and the climate crisis (COLLAÇO, 2019).

The current forms of urban planning have intensified the energy consumption and CO_2 emissions, while the energy planning seeks to raise energy production while simultaneously reducing emissions through an increase of energy efficiency. When dealing with Urban Energy Planning, it is fundamental to reconcile the challenges, strategies and opportunities of both energy and urban scenarios (COLLAÇO, 2019).

Solutions that involve urban morphology and mobility can be a first step towards the definition of strategies linked to energy efficiency in the urban context (MARINS & ROMÉRO, 2012).

UEP has the potential to reduce greenhouse gases and the energy demand in the city, as well as minimize social and environmental injustice. Besides, it promotes energy security through a planning process focused on increasing local renewable energy production. The carbon neutrality and energy transition also positively impact the quality of life of the population, creating the real possibility of reaching more sustainable and resilient cities. Some examples of aspects that impact UEP are the land use and urban density, mobility and transportation, as well as energy demand and urban vegetation. Past political decisions affected these topics and will continue to do so. Unplanned strategies may intensify problems commonly found in populated urban areas such as the Heat Islands Effect, a phenomenon where the temperature is higher in central areas than rural or less populated regions (COLLAÇO, 2019).

As previously mentioned, UEP requires a careful combination between urban and energy planning strategies. In the urban context, one of the main players in the implementation of urban energy planning methods is the public sector, the policy makers, in all levels (city, state and nation) (COLLAÇO, 2019). Nonetheless, it is relevant to emphasize that the transition to a more energy efficient and carbon neutral economy will only be possible if all the sectors are involved (IEA; EPE; MME, 2021). However, this has never been the case in Brazil.

Throughout history, Brazilian urban laws have had some flaws that ended up intensifying a couple of issues. According to WESTIN (2020), back in 1850, the former Emperor of Brazil Dom Pedro II signed the *Lei de Terras* (Land Law, in free translation), a decree that focused on dividing the rural lands in big properties (latifundia) instead of small ones. It ended up increasing and reinforcing the land concentration in the hands of the few richer property owners at the time and left the majority of poor people not only unattended, but also paying high taxes. Land concentration is still a structural problem in the country (WESTIN, 2020).

An accelerated urban process tends to increase resource consumption, highlighting how strongly necessary it is to align both urban and energy planning methods (MARINS & ROMÉRO, 2012). However, when it comes to the combination of strategies from both fields, Brazilian energy policies have never been connected to urban planning and this has been a political choice throughout the years. While the

former comes in the form of initiatives guided by the federal government, such as the Law n. 10.295/2001 (*Lei da Eficiência Energética* ou Energy Efficiency Law, in free translation) (IEA; EPE; MME, 2021), the latter reaches the city scale and gives them enough autonomy to create their own local legislations that regulate the land use and the city expansion in both building and urban scales - documents such as *Plano Diretor, Lei de Uso e Ocupação do Solo, Código de Obras*, examples mentioned by COLLAÇO (2019). This detachment does not smooth the path of a connection between local urban strategies and national energy policies. The governance structure adopted in Brazil sets apart the decisions made in the local and national spheres. As a consequence, according to COLLAÇO (2019), it prevents potential common strategies from even being considered.

In order for UEP to be well constructed and implemented, all the sectors must be involved in the process. Additionally, diagnostic studies must be conducted locally to fully perceive the urban context at hand, as well as opportunities to rip benefits from and challenges to be faced (COLLAÇO, 2019). An example illustrating the importance of analyzing the local scenario first involves the sizes of cities and their current urban development: consolidated cities face bigger difficulties than small towns in terms of energy production, as the latter would be in a more flexible phase to have policies implemented in their territories. Regarding useful tools in this context, modeling has been a helpful aid since the 1970s when applying energy planning to the urban scale (NAKATA, 2004 *apud* COLLAÇO, 2019). Simulation models, for example, seek to create a consistent visualization of energy demand and generation based on the energy system described locally (COLLAÇO, 2019).

The current situation in all the scales addressed in this section offers a compelling and simultaneously crucial opportunity to discuss the impacts that urban growth and energy demand undoubtedly have on one another. The exposed information shows a clear sign that both urban and energy planning strategies are paramount to reduce the negative consequences caused by anthropogenic activities on the planet's ecosystems. Having integrated responses with every sector involved and adding strategic tools in the process can greatly impact the effectiveness of such plans, especially in terms of energy planning and implementation, water and food related-topics, carbon sequestration and urban planning.

In Brazil, it is imperative to create ways to reconcile both local and national policies in order to design pertinent, carefully planned and long-lasting legislations that

comprise energy and urban strategies simultaneously, taking local singularities into account from the very beginning. It is also important to evaluate the real impacts that energy efficiency regulations focused on buildings could have when the point of view is expanded to an urban scenario. Additionally, it is indispensable to involve all the sectors into these processes, from the policy makers to industries and also the general public, so the policies are built by multiple hands and do not prioritize one segment over the other.

2.3 Simulations as a planning strategy

Computer simulation is a powerful instrument to assist the decision-making process by reproducing a scenario that is close to a real-life situation, through the insertion of several parameters, and gathering data to support actions down the line. When applied to the built environment, computer simulations can be used in smaller, more specific scales (for instance, a building) and also in larger urban contexts (city blocks, for example). Variables such as energy performance, thermal comfort, energy demand and emissions can be simulated through softwares. The main goals are to foresee potential issues, identify areas that can be improved in the respective object of study and help formulate the next steps to achieve said result, a feat that is highly helpful during planning phases and before major financial investments are made.

As previously mentioned, modeling has been a useful plan of action since the 1970s when it comes to energy planning in the urban scale (NAKATA, 2004 *apud* COLLAÇO, 2019). And although the method has numerous advantages as cited above, it is important to draw attention to the fact that simulations can reproduce scenarios with a high precision rate depending on the quality of data inserted on them, but are not intended to be taken as the absolute truth. Two main reasons for that can be mentioned: first, since its raw material is data, it is susceptible to inaccuracies and errors; second, they are a representation of reality, not the reality itself. Additionally, it is indispensable for the user to possess a concrete understanding of what is being studied, having the capacity to not only interpret information being inserted in and taken from the simulation tool, but also to identify errors or gaps that need correction. With that being said, computer simulations do contribute considerably in the planning process.

The following subsection dives into several examples of softwares available for both building and urban scale simulations. Although these two scenarios are mentioned to give an initial overview of the topic, the focus remains on the urban sphere and, more specifically, on the software used in the present research: the City Energy Analyst (CEA).

2.3.1 Different perspectives: the building and urban scales

When focusing on the operational part of a simulation process, it is possible to find several softwares on the market destined for a variety of purposes, with free or paid access. However, before choosing a tool, it is imperative that the professional know beforehand about which variables are needed to be evaluated and the scale in which the simulations will be performed. While the former refers to the type of data that will be inserted into the software as input and which results should be expected, the latter relates to the object to be studied, which can go from a single building to multiple city blocks simultaneously. Hence, it is of vital importance to understand the object of study, the results that are expected to be obtained and the methods behind them before deciding for a specific simulation tool.

Table 04 compiles selected examples of softwares available on the market that work in the building and urban scales. Some of the information addressed include the type of access, their target audience and examples of variables analyzed by each one of them. Highlighted in green is the focus of the present research, the software City Energy Analyst (CEA), that will be discussed thoroughly further in this document.

Table 04: Main simulation softwares available on the market

Software	Scale	Platform	Access	Audience	Examples of possible analysis
CEA	**Urban**	Desktop and Web	Free	Architects, urban planners, local authorities	Building solar radiation and energy demand; Life Cycle Assessment: emissions and system costs; energy potentials; networks; supply system optimization.
ENVI-met	**Urban**	Desktop	Paid	Architects, urban planners, universities, local authorities, students	Urban climate scenarios; environmental analysis of cities, buildings and green spaces; short and long wave radiation fluxes; surface and wall temperatures; water and heat exchange, etc.
SimScale	**Urban**	Web	Paid	Similar as mentioned above	Building aerodynamics; indoor and outdoor thermal comfort; pedestrian wind comfort; wind impacts on buildings and urban areas.
Townscope	**Urban**	Desktop	Paid	Similar as mentioned above	Solar radiation; human thermal comfort in open areas; meteorological parameters; visibility.

Urban Microclimate	**Urban**	Desktop	Free	Similar as mentioned above	Effects of urban morphology and geometries on thermal comfort and energy consumption; impacts of the urban heat island effect; hourly urban temperature and humidity.
EnergyPlus	Building	Desktop	Free	Architects, engineers, energy consultants, students	HVAC; thermal comfort analysis; energy efficiency; thermal load simulations, etc.
Climate Studio	Building	Desktop	Paid	Architects, engineers, energy consultants, students	Climate analysis, sun path and shadow studies, daylight analysis, quality views, electric lighting analysis, energy modeling, thermal comfort, natural ventilation, renewable energy performance.
OpenStudio	Building	Desktop (Plug-In)	Free	Similar as mentioned above	Building energy modeling using EnergyPlus; advanced daylight analysis using Radiance; thermal analysis; HVAC, etc.
DesignBuilder	Building	Desktop	Paid	Similar as mentioned above	Daylighting; energy simulations; HVAC; costs; analysis for certification, etc.
Sefaira	Building	Plug-In	Paid	Similar as mentioned above	Energy demand; carbon emissions; thermal comfort; natural lighting; HVAC; costs, etc.
Green Building Studio	Building	Cloud	Paid	Similar as mentioned above	Energy efficiency simulations; carbon emissions; optimization; energy and water use, etc.
IES VE	Building	Desktop	Paid	Similar as mentioned above	HVAC; Building Energy Modeling; daylight and lighting design; US and Canada energy compliance; airflow simulation.

Sources: ETH ZÜRICH, 2023; ENVI-MET, 2023; SIMSCALE, 202-; TOWNSCOPE, 2013; MIT, 202-; ENERGYPLUS, 2023; OPENSTUDIO, 2023; DESIGNBUILDER, 2023; TRIMBLE, 2023; AUTODESK, 2023; IES, 2023; SOLEMMA, 2023 (created and collected by the author).

Most of the softwares listed previously offer paid access, which makes free open-source programs like CEA even more appealing to the public. Another point of comparison is that, broadly speaking, some of the variables are common to almost all of the softwares addressed (thermal analysis and energy demand, for instance), obviously varying the scale, how such variables are considered and the algorithms behind them. As examples of differences among the aforementioned softwares in terms of variables to be considered, while the CEA is able to study the energy

demand of an urban area, its emissions and costs involved, as well as incident solar radiation and potential for energy generation through several technologies, it was not destined to provide urban microclimate analysis like ENVI-met or SimScale, for instance, despite having a specific tab where a weather file can be inserted. Regarding the differences in scale, EnergyPlus thrives when dealing with thermal comfort and energy efficiency analysis. However, said tool was built for simulations on a building scale, not on an urban sphere. Contrasts like the ones mentioned highlight even more the utter importance of considering the necessary variables to be studied and the scale of the study object before deciding which software would be more suitable.

Having the urban-scale simulation tools as the focal point now, besides the general advantages and limitations mentioned before, computer simulation softwares are also a powerful ally in contributing to city planning processes and the improvement of local legislation. According to HONG *et al.* (2020), computer simulation tools fed with rich urban data are able to model a multitude of scenarios in which building performances can be evaluated in order to improve the efficiency and quality of such places, providing valuable information to base the decisions of policy makers, urban planners and stakeholders involved in the process. The simulated variables can comprise energy demands, design and retrofit options, quantification of extreme weather events, among others (HONG *et al.*, 2020).

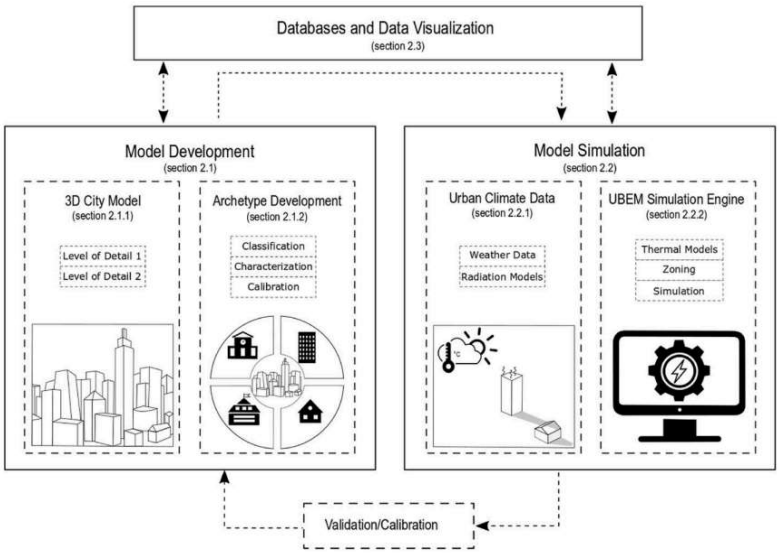
With the possibility of not only modeling and representing reality as it currently is, but also granting the prospect of forecasting future scenarios in the studied area, urban planners and policy makers can visualize how certain strategies may play out years down the line, such as the increase/decrease of building potential in a specific region, impacts of green areas in regions with a high building density, transportation emissions, energy demand (in which UBEM, or Urban Building Energy Modeling, would play an important part as a planning strategy), among others. Diagnosis based on the mentioned data can massively contribute to the improvement of local legislation documents in Brazil, such as Plano Diretor, by providing ways to set data-based strategies for short, medium and long term periods. In even larger scales, the relevance of urban simulations further increases when global agreements towards a more sustainable future are at play, such as the UN 2030 Agenda.

HONG *et al.* (2020) states that Building Energy Modeling (BEM) has been vastly used to illustrate a building performance, prove code compliance and optimize its

operations. When amplifying the scale to a city, the concept of UBEM has been exponentially used, being able to cover from a city block to an entire city. This type of analysis possesses the potential to support design decisions and building optimization, enabling cities to become more resilient. In the energy field, for instance, urban simulations could offer values illustrating how much energy and money could be saved if certain strategies were implemented in the city (HONG *et al.*, 2020). However, when involving analysis of buildings in a collective scale going from a city block, to a neighborhood and then to an entire city, it is crucial to consider the interaction between them and their surroundings. This includes integrating urban datasets and UBEM tools to calculate the studied variables (HONG *et al.*, 2020).

UBEM comprises several steps that can go from modeling the geometric and non-geometric characteristics of a city, to data insertion and the simulation itself. Nevertheless, the modeling procedure is associated with some challenges and uncertainties (JOHARI *et al.*, 2020), as every computer simulation. Image 06 summarizes the step-by-step process when it comes to energy modeling at the city scale. The methods used during the validation/calibration phase aim to address such uncertainties and decrease the chances of major inconsistencies between energy demand and real measurements (JOHARI *et al.*, 2020).

Image 06: Overview of Urban Building Energy Modeling (UBEM)



Source: JOHARI *et al.* (2020)

In addition to considering the building or urban scales during a simulation, it is paramount to also ponder the interaction between them regardless of your object of

study: how they relate to each other and which impacts arise from it, what can be done in order to bring positive effects to both spheres simultaneously, etc.. The individual responsible for running simulations and analyzing results, as well as the policy makers who have impactful decisions over the city, must have a synchronized point of view of both micro and macro scales to be able to understand them and the data gathered thoroughly.

The reasoning built in the present section highlighted some facts of utter importance during simulations: how data is the main feeding element and how its quality directly impacts the relevance of the results; how crucial it is to consider the variables analyzed in a scenario and its scale before choosing the simulation engine, and the theoretical background and critical thinking the user must have to successfully detect possible errors or inconsistencies in the inserted data and results. Regarding data itself, there is another key component to consider: its availability. While in some countries, there are vast databases being fed with suitable and up-to-date local information that can be used in urban simulations, other territories face a lack of sufficient data in some areas to perform this process successfully, such as Brazil. This obstacle is addressed in the following paragraph and through practical experience during the creation of the Brazilian database.

Depending on the type of information needed for a simulation, Brazilian users and researchers often face difficulties due to the lack of sufficient, up-to-date and trustworthy information to insert into softwares. This hindrance is found in several aspects, such as climate data of small towns (BARBIRATO *et al.*, 2011); information related to construction materials that is used for Life Cycle Analysis processes and that can involve data linked to emissions and energy consumption (CASTRO *et al.*, 2015; WITICOVSKI *et al.*, 2018); lack of sufficient information about residential buildings being produced by the real estate market in the last years (LONGARINE & DUARTE, 2017), etc.. Two practical examples of data availability are found in this research: one of the studied cities, Matozinhos, currently does not possess its own weather file, having to rely on one from a different municipality (Belo Horizonte) for the simulations run in this work. A similar lack of information was found in the process of creating the CEA Brazilian database.

2.3.2 City Energy Analyst (CEA)

One of the targets of the present research is analyzing the influence of computer simulations on the urban scale. For this reason, it was necessary to choose a program that could deal with this type of scenario while also analyzing relevant variables in the built environment context, such as emissions, energy consumption and demand. Therefore, the City Energy Analyst, or CEA, was chosen to run the simulations. It is also worth mentioning that CEA 3.34.2 was the software version used for the present research due to some incompatibilities found between its latest version and the computer used for such tasks. Therefore, any additions or modifications performed by the developers on the newest versions (the most recent up to this moment being version 3.37.x) are not addressed in this work.

The focus now is on detailing CEA from a theoretical standpoint, going from its context and applicability to the characterization of its database, analyzed variables and operability. As an example of a free open-source software, CEA offers its users a relevant range of possibilities for analysis within the realm of the built environment, producing substantial data to base decision-making processes that can impact considerably the urban fabric and even local legislations. To put its value into perspective, of all the urban tools and models surveyed by JOHARI *et al.* (2020), the CEA was able to produce the most far-reaching combination between UBEM and urban models due to the simulation software being made of several specific modules, aspect that will be covered in depth in the following subsections.

The CEA is able to analyze several city blocks simultaneously, being a powerful tool to provide ways of investigating current and forecasting future scenarios in an urban area through computer simulations that deal with variables going from emissions to energy demand, energy generation potential, among others. When considering the fast urban transformations and the need for more sustainable planning and development processes, tools like CEA are relevant assets to the decision-making moments of policy makers, urban planners, architects and other professionals involved. Additionally, as mentioned in the beginning of the simulations section, characteristics like the ones cited put CEA in the position of a considerably helpful tool for the improvement of local legislations, such as *Plano Diretor* and Energy Efficiency Codes, since it is possible to study the impacts that an increase or

decrease of building density in a specific region could have on the local energy demand and the potential for solar energy production, for instance.

2.3.2.1 Contextualization and applicability

Developed by researchers Prof. Dr. Arno Schlueter, Dr. Jimeno A. Fonseca and Daren Thomas at ETH Zürich, in Switzerland (CITY ENERGY ANALYST, 2017), CEA is a computational framework focused on analyzing and optimizing energy systems in neighborhoods and cities (FONSECA *et al.,* 2016). The software enables its users to make energy demand and supply analysis for buildings at a district scale (HONG *et al.*, 2020) and also allows them to study carbon emissions and financial advantages in several urban scenarios. Furthermore, it includes the possibility of analyzing distributed energy generation (FONSECA *et al.,* 2016). CEA integrates time-dependent methods in order to simulate building energy performance, assessment of local energy potentials, bi-level energy systems optimization and analysis based on multiple criteria (FONSECA *et al.*, 2016). One example of an engine that was adapted to solar radiation studies and was also integrated in later versions of CEA is Daysim, a daylight analysis software (JOHARI *et al*., 2020).
CEA can offer relevant assistance in regards to improving energy systems, retrofitting buildings and analyzing renewable energy potentials in the studied area, for instance (FONSECA *et al.*, 2016). Another strong asset to be highlighted, compared to other urban simulation tools, is that CEA offers a user-friendly interface, as illustrated by Image 07. It helps users to better understand which variables are being analyzed by the tool and also improve results visualization.

Image 07: CEA interface when a project is open

Source: The author.

CEA offers two desktop possibilities when installed: the main software, called “CEA Dashboard”, and the “CEA Console”, where programmers and other users can collaborate with the development of the program. Nowadays, it also offers a cloud-based version, hosted directly on the software website. Regarding its programming language, FONSECA *et al.* (2016) mentions that CEA was written in the open-source Python v2.7. In terms of obtaining the 3D building shapes to be used in the simulations, the software provides two possibilities: it can gather the existing shapes and the city conformation from OpenStreetMap, a free, editable and open geographic database maintained by volunteers through open collaboration (OPENSTREETMAP, 2022) or the user can opt for importing shapefiles (.shp format) from QGIS or ArcGIS into CEA. These different methods can impact positively or negatively the precision of the modeled data.

A software with such potential as CEA is especially relevant due to the modern challenges and targets for a more sustainable urban planning, especially involving the concept of Urban Building Energy Modeling. FONSECA *et al.* (2016) highlight the importance CEA has in assisting urban authorities and policy makers during the decision-making process in order to improve the performance of cities, from both a design and an engineering standpoint.

2.3.2.2 Analyzed variables and possible results

CEA main workspace displays some important buttons on the left-hand side, where it is possible to set parameters in order to properly run the simulations. They are named as follows: “Project Overview”, where existing projects are opened and new scenarios can be created; “Database Editor”, where information from the chosen database for the simulations can be altered; “Input Editor”, where the 2D/3D studied area extracted from OpenStreetMap can be visualized and fundamental parameters, such as typology, architecture and internal loads, can be altered; “Tools”, another working tab where all the variables offered by the software can be chosen by the user to be simulated (see Table 05 for the variables) and, lastly, the “Dashboard”, where results generated by the simulations are displayed in form of graphs.

Table 05: Available variables in the “Tools” button

Subtab	Options	Purpose
DATA MANAGEMENT	Archetypes Mapper	Assign building properties and systems types. It involves the input databases linked to comfort, architecture, air-conditioning, internal loads, supply systems and schedules, all tabs found in the “Input Editor” button.
	Weather Helper	Place where the user sets the local weather file for a scenario.
	Surroundings Helper	Query geometry of surrounding buildings from OpenStreetMap.
	Terrain Helper	Query topography with a fixed elevation.
	Streets Helper	Query streets geometry from OpenStreetMap.
DEMAND FORECASTING	Building Solar Radiation	Calculation of solar radiation using Daysim. There are two options: one more complete and another, simplified/beta.
	Building Schedules	Set schedules the occupancy profile of buildings.
	Building Energy Demand	Calculate the energy demand.
LIFE CYCLE ANALYSIS	Emissions	Emissions and primary energy due to building, construction, operation, dismantling and induced mobility. Operation and embodied emissions.
	System Costs	Costs due to supply systems.
ENERGY POTENTIALS	Shallow Geothermal Potential	Heat extracted from geothermal probes (up to 50m length).
	Water Body Potential	Heat extracted from a lake or water body.
	Photovoltaic-thermal Panels	Electricity and heat production from Photovoltaic / thermal technologies.
	Photovoltaic Panels	Electricity production from solar PV technologies.
	Sewage Heat Potential	Heat extracted from the sewage heat exchanger.
	Solar Collectors	Heat production from solar collector technologies.

NETWORKS	Thermal Network Part I (Layout)	Create a potential layout of the network with the minimum spanning tree.
	Thermal Network Part II (Simulation)	Solve the thermal hydraulic network.
OPTIMIZATION	Supply System Part I (Decentralized)	Run optimization for decentralized operation.
	Supply System Part II (Centralized)	Run optimization for centralized operation.

Source: CEA 3.34.2. Compiled by the author.

In the "Input Editor", there are 09 tables containing part of the data to be used for the simulations. They can either come from OpenStreetMap (such as building height and number of floors) or from the software's own database. These tables are briefly described in Table 06.

Table 06: Input Editor tables (CEA 3.34.2)

Table	Brief description and type of data presented
Zone	Number of floors above and below ground, floor height and address.
Typology	Construction year and standards, building uses and fraction of gross floor area.
Architecture	Construction physical characteristics (types of external and internal walls, roofs, floors, shading devices, windows, window-to-wall ratio, building tightness, etc.).
Internal loads	Information such as occupation density, electrical load due to computers, peak specific daily hot water consumption, etc.
Indoor comfort	Data linked to cooling and heating systems (setpoint and setback point temperatures), as well as upper and lower bounds of relative humidity.
Air-conditioning systems	Data regarding HVAC (heating, ventilation and air-conditioning) systems.
Supply systems	Data involving cooling, heating, electricity and hot water supply assemblies.
Surroundings	Lists all the buildings encircling the studied area.
Schedules	All occupation schedules for each use listed in the chosen database.

Source: Compiled by the author.

The subtab "Data Management", mentioned in Table 05, contains the first scripts to be run in each scenario, one of them being the Archetypes Mapper. It assigns properties to the buildings and systems involved in the simulation and gathers data from the input databases regarding comfort, architecture, air-conditioning, internal loads, supply systems and schedules, part of the tabs mentioned in Table 06. An important disclaimer is that, if the user runs these five initial scripts, modify the named tables on "Input Editor" and then proceed to run the scripts again, the alterations made will be lost and the definitions will be reset to default.

After correctly setting up the input data in the “Data Management” subtab, running the initial scripts and also defining the additional information presented in the tables located in the "Input Editor" button, the user can proceed and run the simulations listed in the other subtabs in Table 05 (“Demand forecasting”, “Life Cycle Analysis”, “Energy Potentials”, “Networks” and “Optimization”). Each one of them will have a collection of information that can be altered by the user. Once the desired simulations are finished, the results can be displayed as graphs and charts in the "Dashboard" option. There, the user can create a dashboard in which each graph or chart can be visualized. Table 07 lists the possible results to be gathered and turned into graphs directly from the software.

Table 07: Available results in the “Dashboard” button (CEA 3.34.2)

Category	Plot	
SCENARIO COMPARISONS	Annualized costs; Annualized emissions	
ENERGY DEMAND	Comfort chart; Energy Balance; Energy End Use; Energy End-Use Intensity; Energy Final Use; Energy Final Use Intensity; Heating Reset Schedule;	Load Curve; Load Curve Supply; Load Duration Curve; Load Duration Curve Supply; Peak Demand; Peak Supply
OPTIMIZATION	Pareto Curve; Parallel coordinates; Annualized costs;	Annualized emissions; Investment costs; Performance of optimization algorithm
SOLAR POTENTIALS	Solar radiation	

SUPPLY SYSTEM	Supply system map; Installed capacities; Requirements curve electricity; Dispatch curve electricity;	Dispatch curve heating plant; Dispatch curve cooling plant; Impact on Electrical Grid (ramp-rate)
TECHNOLOGY POTENTIALS	Photovoltaic Potential; PVT Electricity/Thermal Potential Solar Collector (ET) Potential	
THERMAL NETWORKS	Network Layout at Nominal Operating Conditions; Load curve of heat and pressure losses; Yearly energy consumption; Thermal losses and pumping requirements per pipe; Heating reset curve; Pumping duration curve	

Source: CEA 3.34.2. Compiled by the author.

Besides weather files, as pointed out by Table 05, CEA also offers its own databases to be used in simulations. In the software version used in this research (3.34.2), two options of databases with building and systems information are available: the Swiss one (CH), destined to countries with temperate countries, and the Singaporean database (SG), focused on hotter climates (ETH ZURICH, 2023). The latter will be the case study of the present research due to the characteristics of Brazilian weather. Additionally, in terms of its structure, the Singaporean database was used as a model to be followed during the creation of the Brazilian one.

2.3.2.3 Characterization of the existing database

As the Singaporean database will be the case study of this research, a brief contextualization of the location is needed.

Singapore is a small, low-lying and tropical island located in South-East Asia. The city-state has a population of 5 million people, majorly from the Chinese, Malay, Indian and Eurasian communities. Strategically positioned, Singapore offers high quality infrastructure and diverse culture for its inhabitants and tourists. Due to its physical characteristics, limited land access and a lack of natural resources, the island is vulnerable to the impacts imposed by the climate emergency. Therefore, Singapore has a practical understanding of the challenges of sustainable development, being a supporter of the UN 2030 Agenda (SINGAPORE, 2023).

In regards to the Singaporean database, it was noted during its analysis that the set of files is structured in three main folders named “Archetypes”, “Assemblies” and “Components”. In summary, the first one includes tables with data regarding envelope characteristics, HVAC assemblies, supply assemblies and information about building occupation schedules; the second folder contains tables with data linked to construction elements, shading devices, HVAC for cooling and heating, ventilation and electricity, as well as data regarding supply systems; and the last one comprises data about energy and electricity sources, as well as distribution. Image 08 highlights the current content of a folder named “Use_types”, found in the “Archetypes” main folder.

Image 08: Folder “Use_types” in “Archetypes”, with its current content.

Source: Singapore database folder, CEA version 3.34.2.

Additionally, Image 09 illustrates the type of information that can be found in the “Envelope” table, one of the files of the “Assemblies” folder.

Image 09: Example of the data addressed in the "ENVELOPE" table, found in the "Assemblies" folder.

Description	code	U_win	G_win	e_win	F_F	GHG_WIN_kgCO2m2
single glazing	WINDOW_AS1	4,8	0,85	0,89	0,2	47
double glazing	WINDOW_AS2	3,1	0,75	0,89	0,2	62
double glazing - with argon filling	WINDOW_AS3	1,3	0,75	0,89	0,2	69
double glazing with low-emissivity coating	WINDOW_AS4	1,1	0,67	0,02	0,2	123
triple glazing	WINDOW_AS5	0,99	0,7	0,89	0,2	123
trple glazing with two selective low-emissivity coatings	WINDOW_AS6	0,6	0,5	0,02	0,2	123
double window	WINDOW_AS7	1,2	0,75	0,89	0,2	70
single glazing - HDB	WINDOW_AS8	5,4	0,85	0,89	0,2	47
window - NTU	WINDOW_AS9	1,8	0,29	0,89	0,2	62
window - SinBERBest Office	WINDOW_AS10	2,2	0,2	0,89	0,2	62

CONSTRUCTION | TIGHTNESS | WINDOW | ROOF | WALL | FLOOR | SHADING

Source: Singapore database folder, CEA version 3.34.2.

The SG database comprises information to correctly describe Singaporean scenarios in terms of building characteristics, air-conditioning systems, emissions, building schedules, energy sources, energy generating equipment, among others. And as previously stated, it is also destined to other hot climate nations. Table 08 lists the content of each of the three main folders located in the SG database.

Table 08: Files in the SG database

Main folder	Secondary folder	Contents
ARCHETYPES	USE_TYPES	• 19 .csv files with use schedules (FOODSTORE, GYM, HOSPITAL, HOTEL, INDUSTRIAL, LAB, LIBRARY, MULTI_RES, MUSEUM, OFFICE, PARKING, RESTAURANT, RETAIL, SCHOOL, SERVERROOM, COOLROOM, SINGLE_RES, SWIMMING and UNIVERSITY); • 01 informative note (.txt file); • USE_TYPE_PROPERTIES (Excel table).
	–	CONSTRUCTION_STANDARD (Excel table)
ASSEMBLIES	–	ENVELOPE (Excel table); HVAC (Excel table); SUPPLY (Excel table); SUPPLY_NEW (Excel table).
COMPONENTS	–	CONVERSION (Excel table); CONVERSION_NEW (Excel table); DISTRIBUTION (Excel table); ENERGY_CARRIERS (Excel table); FEEDSTOCKS.

Source: CEA 3.34.2. Compiled by the author.

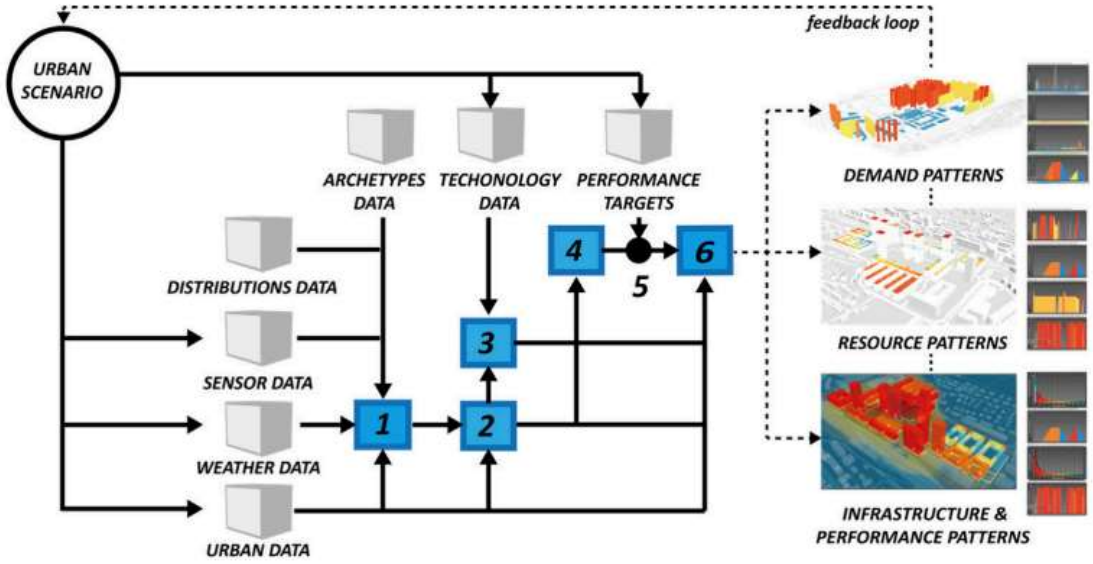
In order to create the Brazilian database, the SG one was analyzed thoroughly, table by table, as the methodology chapter of this research describes in detail. Additionally, the variables addressed were checked in order to see which ones were applicable to

the Brazilian scenarios studied in this research and which ones were not. The main goal was to understand the nature of the information included in the original database and list its contents to, then, create the Brazilian version within the same logic, but with local data whenever possible.

2.3.2.4 Software operation

Concerning its operation methodology, FONSECA *et al.* (2016) state that CEA uses seven databases featuring information linked to the urban area, weather, sensors, distributions, archetypes, technology and performance targets. Additionally, it also comprises six calculation modules, as presented by Image 10: from 1 to 6, demand module, resource potential module, systems technology module, system optimization module, decision module and spatiotemporal analysis module.

Image 10: CEA framework



Source: FONSECA *et al.* (2016)

According to FONSECA *et al.* (2016), each of the seven databases mentioned previously can be briefly described as follows:

1. The urban database stores geo-referenced information of buildings, infrastructure, topography and local resources gathered from OpenStreetMap. Additionally, data such as buildings footprint area, height, occupancy patterns, last time it went through renovation and window-to-wall rations are shown and can also be manually altered. It also features information regarding local

energy networks, roads, water and soil characteristics and a digital elevation showing the topography of the chosen area;

2. The weather database comprises time-series data of temperature, relative humidity and solar transmissivity;
3. The sensor database contains information about energy services in buildings that are not standardized;
4. The distributions database stocks standard time-series information for all the building types presented in the archetype database. This includes figures such as occupancy schedules, minimum ventilation rates, temperature and humidity set points, hourly consumption values for appliances, lighting, among others;
5. The archetypes database compiles information regarding standard properties of local building stock, including their envelope and HVAC systems. This database was built based on statistical data gathered for buildings completed before 2005. Years beyond that have values gotten from linear interpolation and local building regulations, according to FONSECA *et al.* (2016);
6. At last, the target database contains percentages of decision criteria and key performance values in order to guide the selection of infrastructure options;
7. The metrics database is made of economic and technical metrics of conversion, distribution and storage technologies (FONSECA *et al.*, 2016).

In terms of hierarchy, FONSECA *et al.* (2016) state the latter takes the district scale into account. Since this concept is not commonly used in Brazil, both the Brazilian database and the areas chosen to be simulated in this research did not use this definition whatsoever, opting for adapting it to the local context: the database considers the building and city scales (with the former also being considered by CEA), while for the simulations the simple concept of city blocks was also used.

Concerning the modules, the decision one includes a multi-criteria decision analysis aiming to boost the social, environmental and economic potential of the studied area. It also takes into account six sub-criteria, such as penetration of renewables in the area, total annual energy costs and operational costs, emissions, among others.

With the simulation software formally presented and explained, the next step is to contextualize the two Brazilian cities that were chosen to be studied using CEA: Belo Horizonte and Matozinhos, both located in the state of Minas Gerais.

2.4 The Brazilian context: introduction and motivations

The following section addresses some important characteristics of the areas chosen for this research, namely Belo Horizonte, the capital city of Minas Gerais, and Matozinhos, a small town near the same region. Before discussing said cities, a brief contextualization of the metropolitan region where they are located is given. As for the motivations to choose these places, three main reasons are listed:

1. Geographical proximity: the fact that both cities are considerably close to each other allows similar characterizations in some aspects, such as prominent construction types and climate;
2. CEA database: with geographically close cities, it is possible to use the same database for both without gravely compromising the accuracy of the results. The CEA databases take into account variables that deal with prominent construction types, air-conditioning strategies, among other factors. Therefore, choosing cities with similar characteristics would favor the use of the same database - in this research, the original SG and the recently created BR;
3. Different urban densities: the difference between both locations in terms of building density and population is also a desirable trait for the present research. While Belo Horizonte is a highly populated and urbanized location, Matozinhos is a small municipality in terms of its inhabitants and building density. The hypothesis formed in this case was that this situation would enable interesting results during the simulations, which would allow comparisons in two different scenarios.

The following sections create a profile of the urban areas defined for this research, starting off with the larger urban conglomerate - Belo Horizonte Metropolitan Area - in order to give an introductory context of the urban surroundings the two chosen cities are inserted in. Subsequently, the discussions proceed to the city scale, addressing both Belo Horizonte and Matozinhos.

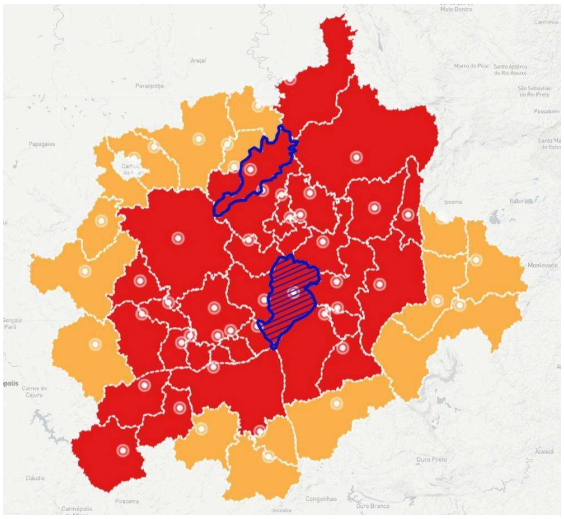
2.4.1 Characterization of the urban areas

The descriptions of each of the two cities selected for this research covers some common points to enable a more direct comparison between them. Such aspects include their urban conformation, population density, most common construction techniques and climate. However, before getting to them individually, it is relevant to give context to the urban region to which they are a part of.

2.4.1.1 Belo Horizonte Metropolitan Area

The Greater Belo Horizonte is composed of 34 cities with different sizes, population and economic relevance. Image 11 illustrates in red the member cities of said region and, in orange, the towns that are part of what is called the “Metropolitan Belt” (*Cinturão Metropolitano*, in Portuguese). Belo Horizonte (hatched in blue) and Matozinhos are highlighted.

Image 11: Greater Belo Horizonte and the Metropolitan Belt.



Source: Plano Metropolitano RMBH, 2023. Adapted by the author.

The following table presents basic information related to the Greater Belo Horizonte, from its combined population and territorial area to its biome. During the contextualization of Belo Horizonte, it will be noticeable the tremendous importance the capital city possesses over this region, as its individual Gross Domestic Product calculated in 2010 accounted for almost 88% of the total GDP of the other thirty-three member cities combined.

Table 09: Basic characteristics of the Greater Belo Horizonte region

Basic characteristics of the Greater Belo Horizonte (*RMBH* in Portuguese)	
Member cities (34 in total)	Belo Horizonte, Baldim, Jaboticatubas, Taquaraçu de Minas, Nova União, Caeté, Sabará, Santa Luzia, Lagoa Santa, Pedro Leopoldo, Matozinhos, Capim Branco, São José da Lapa, Confins, Vespasiano, Raposos, Rio Acima, Nova Lima, Contagem, Ribeirão das Neves, Esmeraldas, Florestal, Juatuba, Brumadinho, Ibirité, Sarzedo, Mário Campos, Betim, Igarapé, São Joaquim de Bicas, Rio Manso, Itatiaiuçu, Mateus Leme and Itaguara.
Population (2020)	6.006.091 people
Area	**9,470.72 km²** *A.N.: Calculated by the author based on information gathered from the IBGE (Brazilian Institute of Geography and Statistics) website.*
GDP *per capita* (2010)	R$24,740.93
Biome (2012)	Cerrado, Atlantic Forest, Campo Rupestre de Altitude
Altitude (range)	601-900 and 901-1200 m above sea level (FERREIRA *et al.*, 2019)

Sources: IBGE, 2020; IPEA, 2015; GOVERNO ESTADUAL, s.d.; RMBH, 2023; FERREIRA *et al.*, 2019 (created and collected by the author).

With the basic contextualization of the larger urban reality Belo Horizonte and Matozinhos are inserted, the following subsection addresses the main city of said metropolitan region.

2.4.1.2 Belo Horizonte

The capital city of Minas Gerais is located in the central portion of the state. It is also positioned in a privileged region in terms of renewable energy potential, especially when it comes to solar power, as seen in the previously addressed segments and also further in the present subsection. However, before approaching said topic, it is pertinent to describe the city with its physical and climate-related attributes, as summarized by Table 10.

Table 10: Physical and climate-related attributes of Belo Horizonte

Physical and Climate-Related Attributes of Belo Horizonte	
Geographical coordinates	19.921 S; 43.938 W
Population (2022)	2.315,560 people (2021 estimation)
Territorial area (2021)	331.35 km²
Population density (2022)	6.988,18 people per km²
Urban area (2019)	274.04 km²
GDP *per capita* (2010)	R$21,750.94
Topography and territory cover	Variable, with hills in its landscape and significant slopes in some areas. According to the City Council, the average slope is 8.28% (around 4.73°). In regards to the use of the territory and its covering, it is possible to define the following percentages: ● Area with no vegetation (2021): 27,033 acres (81.59%); ● Area destined to agriculture (2021): 1,968 acres (5.94%); ● Forests (2021): 1,958 acres (5.91%); ● Non-forestry natural formation (2021): 1,943 acres (5.86%); ● Water body (2021): 232 acres (0.70%). Territory use characteristics: ● Anthropic: 28,930 acres (87.31%); ● Natural: 4,133 acres (12.48%).
Biome (2019)	Cerrado, Atlantic Forest
Average altitude	895 meters above sea level
Weather characteristics	The wet season is humid and overcast, while the dry season is generally represented by warm weather and clear skies.
Average temperatures	Typically, it ranges from 13°C (55°F) to 29°C (84°F)
Annual average precipitation	1.500 mm (1500 liters of water in 1 m²). In general, the wetter season lasts 5.3 months (october-march) and the drier one, 6.7 months (march-october), with July being the driest month of the year.
Adequate sewage systems rate	96.2%

Sources: IBGE, 2022; Mapbiomas, 2021; Weatherspark,20--.; PBH, 2020

(created and collected by the author).

Diving deeper into climate-related characteristics, Table 11 summarizes the Climate Normals of Belo Horizonte from 1991 to 2020. This three-decade compilation of climatological variables is a valuable set of data for public and private institutions, scientists and the agriculture industry to understand the climate behavior of the studied area throughout the years (INMET, 2023). As a consequence, planning strategies in each of their fields can be better built and implemented. The following

table introduces information such as predominant wind direction through the year in Belo Horizonte, average annual temperatures, radiation and precipitation.

Table 11: Examples of Belo Horizonte Climate Normals from 1991 to 2020

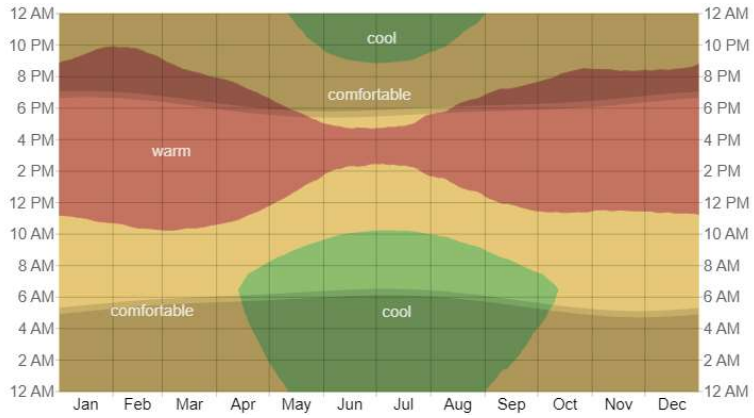
Potential Evapotranspiration (mm)	Annual: 1496.2 mm; Minimum: 79.2mm (June) Maximum: 158.4mm (Jan.)	**Resultant Wind Direction** (degrees)	Annual: 117 °
Predominant Wind Direction	Annual: East	**Wind Intensity**	Annual: 1,5 $m.s^{-1}$
Compensated Relative Humidity	Annual: 63.7% Minimum: 54% (August) Maximum: 71% (Dec.)	**Days with monthly and annual min. temperature < 10°C**	0 days
Monthly and annual minimum temperature	Annual: 18 °C Minimum: 15.2 °C (July) Maximum: 20.2 °C (Feb.)	**Days with monthly and annual max. temperature > 40°C**	0 days
Monthly and Annual Wet Bulb Temperature	Annual: 18.2 °C Minimum: 15.4 °C (July) Maximum: 20.2 (Jan./Feb.)	**Monthly and Annual Compensated Average Temperature**	Annual: 22.1 °C Min.: 19,4 ºC (July) Max. = 24 °C (Feb.)
Days with monthly and annual max. temperature > 35°C	Annual: 1 day (October)	**Days with monthly and annual max. temperature ≥ 30°C**	Annual: 75 dias (All months, except for May, June and July)
Monthly and Annual Maximum Temperature	Annual: 27.3 °C Min.: 24.9 °C (June/July) Max.: 29.1 °C (February)	**Atmospheric Pressure at the level of the barometer**	Annual: 913.6 hPa
Days during the month or year without precipitation (≤ 1mm)	Annual: 276 days Min.: 15 days (Dec.) Max.: 30 days (July/Aug.)	**Days during the month or year with precipitation ≥ 100mm**	0 days
Days during the month or year with precipitation ≥ 10mm	Annual: 49 days Min.: 0 days (June/July/Aug) Max.: 10 days (December)	**Days during the month or year with precipitation ≥ 5mm**	Annual: 67 days Min: 0 days (July) Max.: 13 days (Dec)
Monthly and Annual Cumulative Precipitation	Annual: 1578.3 mm Min.: 5.4 mm (July) Max.: 339.1 (December)	**Monthly and Annual Cloudiness**	Annual: 0.5 Min.: 0.3 (Jun-Aug) Max.: 0.7 (Dec-Jan)
Total Insolation	Annual: 2427.8 h Min.: 162 h (December) Max.: 244.8 h (August)	**Total evaporation**	Annual: 1808.5 mm Min: 131 mm (June) Max.: 195 mm (Sept)

Source: INMET, 202- (created and collected by the author).

Image 12 complements the mentioned tables by displaying the average hourly temperature in Belo Horizonte. The warmest moments tend to concentrate in the

afternoon of the first and last four months of the year, while the period with satisfactory thermal comfort resides throughout the year, in the morning and at night.

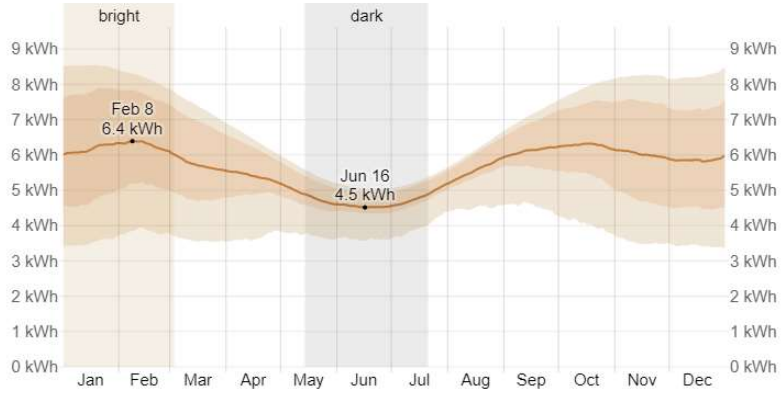
Image 12: Average hourly temperature in Belo Horizonte



Source: Weatherspark.com.

Regarding its solar energy potential, Image 13 illustrates the average daily incident shortwave solar energy in Belo Horizonte. It represents the energy reaching the ground surface over a wide area, considering variables such as seasonal fluctuations throughout the year, the elevation of the Sun above the horizon and the absorption by clouds and other atmospheric components. Shortwave radiation includes ultraviolet (UV) radiation and visible light (WEATHERSPARK, 20--).

Image 13: Average daily incident shortwave solar energy in Belo Horizonte.



Source: Weatherspark.com

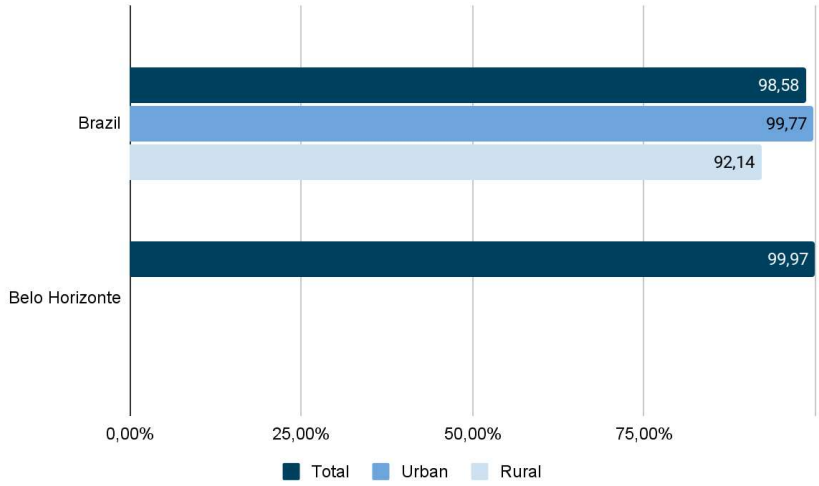
The brighter period of the year in the city lasts around two months, from January to March, with average values reaching 6.4 kWh of incident shortwave energy per square meter in February. On the other hand, the darkest period of the year generally goes from May to July, with June being the darkest month in Belo Horizonte. The

average daily incident shortwave energy in this period reaches values around 4.5 kWh (WEATHERSPARK, 20--).

As mentioned in the energy section, Minas Gerais has buildings predominantly made of brickwork with external coating, reaching 72% of the total surveyed properties (ELETROBRÁS, 2019), a tendency that repeats itself when considering the national scale: wall systems based on concrete or ceramic blocks represent the majority of external walls in Brazilian households (IBGE, 2018; ELETROBRAS, 202-). Considering Belo Horizonte only, data has been found to corroborate with said tendency. A government website called "Atlas Brasil" presents information regarding the percentage of households with walls that are not composed of brickwork or dressed timber. The last available year with information about this topic dates back to 2010 and it pointed out that only 0.15% of households in Belo Horizonte would not be composed of brickwork or dressed timber. To put into perspective, Brazil had 3.42% of households within the same scenario in that year (ATLAS BRASIL, 2022).

In terms of HVAC systems in Belo Horizonte, no specific data was found in regards to the predominant air-conditioning systems in buildings up to the present moment. When it comes to households with access to electricity, Belo Horizonte presents even higher rates than the country, as summarized by Graph 08 with data gathered in a survey back in 2010, once again the last available year with said topic.

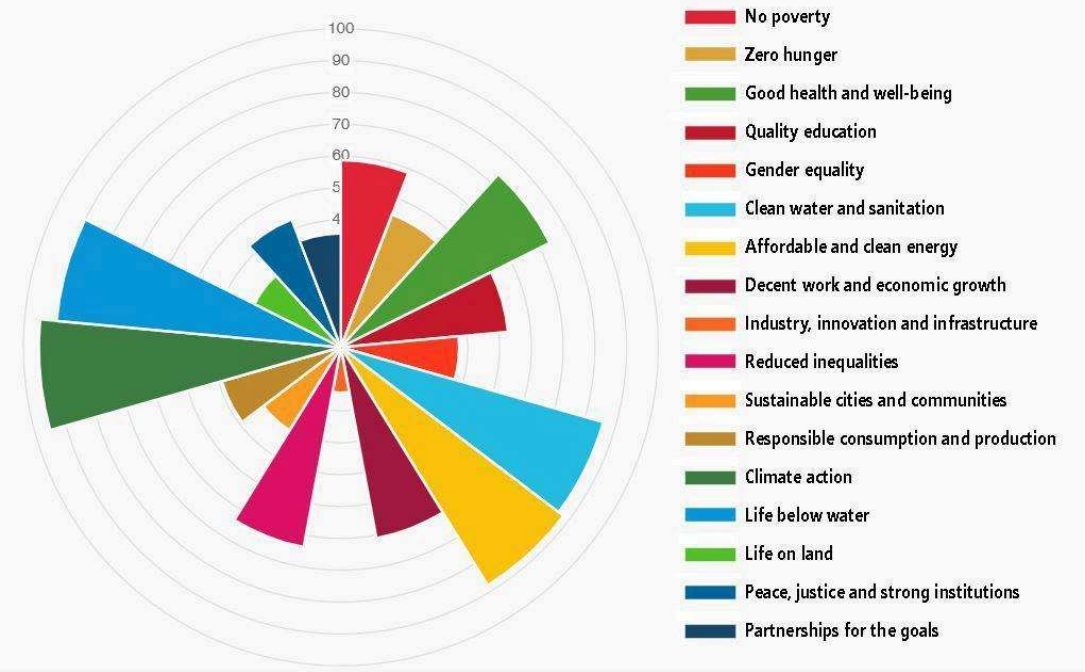
Graph 08: % of people in households with access to electricity - *Censo* 2010.



Source: ATLAS BRASIL, 2022. Created by the author.

Belo Horizonte has also been trying to tackle the UN Sustainable Development Goals in its territory, as shown by Image 14.

Image 14: Performance per goal in Belo Horizonte. Data in %.



Source: IDSC, 202-. Adapted by the author.

According to data provided by the IDSC Brasil (Cities Sustainable Development Index, in free translation), the city is ranked at 481st place in a total of 5570 analyzed cities, with 55.53 points in a total of 100. This puts the city into a medium level of sustainable development.

The highest ranked goals are numbers 6 (Clean water and sanitation), 7 (Affordable and clean energy), 13 (Climate action) and 14 (Life below water), although it is relevant to highlight in regards to the latter that Belo Horizonte is not a coastal city, but it does have water bodies in its territory. On the other hand, the objectives with the lowest development index are currently numbers 5 (Gender equality), 9 (Industry, innovation and infrastructure), 11 (Sustainable cities and communities), 12 (responsible consumption and production), 15 (Life on land) and 17 (Partnerships for the goals).

Some observations are relevant to be made. First of all, some of the lowest ranked goals in the city involve urban planning in some capacity, namely goals number 9, 11 and 12. Additionally, one of the goals with the highest development index deals with renewable energy (number 7). Both facts show a potential for local improvement if the logic of Urban Energy Planning were correctly implemented in the city. It also

highlights the relevance of an urban energy planning tool, such as CEA, to aid in this process.

Closing in on the scale, two areas of Belo Horizonte were chosen to be studied in the present research: sections of the neighborhoods *Lourdes* and *Céu Azul*, the former being an economically thriving region near downtown Belo Horizonte and the latter, a predominantly residential vicinity considerably distant from the central area. Image 15 illustrates the two sections outlined by a red contour, which was the initial definition of area to be studied, and a lighter red spot, limiting the actual regions that were simulated. The reason for such reduction was a combination between the remaining time frame for the present research and the substantial amount of data that would need to be dealt with, since the building settings on CEA must be altered individually in order to improve the precision of results.

Image 15: Sections of Lourdes (left) and Céu Azul (right) chosen to be simulated on CEA.

Source: CEA. Modified by the author.

Through a tour made via Google Street View, as briefly exemplified by Image 16, it is noticeable that *Lourdes* can be described as an upper middle class neighborhood closely located to downtown Belo Horizonte, with multi-story buildings in most of its area and a high population density.

Image 16: Partial view from *Lourdes*.

Source: Google Street View

In terms of building uses, its diversity ranges from residential to commercial buildings, as well as offices, drugstores, supermarkets, health units, parking spaces, teaching institutions such as schools and universities, restaurants, among others. There are also multi-use buildings in this area, such as multi-story ones where the ground floor is occupied by retail services and the upper floors are residences. *Lourdes* is a considerably well served neighborhood in terms of urban infrastructure.

Regarding construction characteristics, the region tracks with what was introduced in the energy section of this research, having a massive portion of its buildings made of masonry walls and concrete structures. In terms of air conditioning, although there is no local survey with this type of data at the moment, it is possible to notice HVAC systems in the façades of a few high rise buildings through Google Street View, as exemplified by Image 17. In the area chosen to be studied, 112 buildings spread in 6 blocks were simulated.

Image 17: Example of a building in the studied area with visible HVAC systems.

Source: Google Street View

The second studied area, *Céu Azul*, presents considerably different characteristics compared to *Lourdes*, as shown by Image 18. The former is a predominantly residential area in Belo Horizonte, although it does possess small-scale retail places and other types of services in fewer numbers, such as barber shops. It has a lower population density and its buildings do not reach high altitudes, with the studied area presenting buildings with one to three floors in most cases.

Image 18: Partial view from *Céu Azul*.

Source: Google Street View

The construction systems have similar natures, most of them being masonry walls and concrete structures, but the construction standards vary greatly from the previous neighborhood: in this area, for instance, there are some examples of buildings with unfinished external walls. Additionally, in this area a specific type of construction was also found and chosen to be part of the simulations as well:, what, in Brazil, is known as “self-construction”, buildings that were made by individuals without any technical guidance nor approval by the local authorities. For the purposes of this research and in order to use an impersonal term free of possible prejudiced views, these types of buildings are referred to as “atypical settlements” in both the BR database and the discussions in this document.

Through a tour via Google Street View, it is noticeable that the neighborhood is served with urban infrastructure. In total, 94 buildings spread through 1 block were simulated in the mentioned section of *Céu Azul*. Both regions will be mentioned again in the methodology chapter, along with the selected area in Matozinhos.

2.4.1.3 Matozinhos

Matozinhos is a city in the central area of Minas Gerais, around 50 km far from Belo Horizonte, with a population of over 37,000 people and an area of 252,45 square kilometers. Table 12 introduces the city with information regarding its physical, urban and climate attributes.

Table 12: Physical and climate-related attributes of Matozinhos

Physical and Climate-Related Attributes of Matozinhos	
Geographical coordinates	19.5653 S, 44.0787 W
Population (2022)	37,618 people
Territorial area (2022)	252,45 km²
Population density (2022)	149,01 people per km²
Urban area (2019)	13.30 km²
GDP *per capita* (2020)	R$30,372.03
Topography and territory cover	Variable. In regards to the use of the territory and its covering, it is possible to define the following percentages: ● Area with no vegetation (2021): 1,550 acres (6.14%); ● Area destined to agriculture (2021): 15,398 acres (61%); ● Forests (2021): 7,813 acres (30.95%); ● Non-forestry natural formation (2021): 319 acres (1.26%); ● Water body (2021): 164 acres (0.65%).
Biome (2019)	Cerrado
Average altitude	792 meters above sea level
Weather characteristics	The wet season is humid and overcast, while the dry season is mostly clear and warm year round.
Average temperatures	Typically it varies from 13°C (56°F) to 28°C (83°F), rarely reaching below 10°C (50°F) or above 32°C (90°F).
Average precipitation	96 mm *(A.N.: Value obtained by adding up monthly values in a year and dividing them by 12)*.
Adequate sewage systems rate (2010)	67.2%

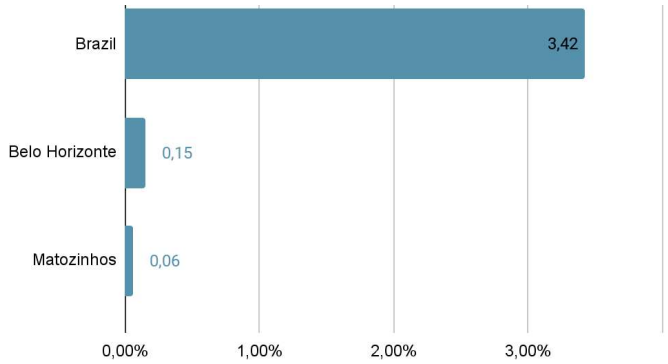
Sources: IBGE, 2022; Mapbiomas, 2021; Weatherspark,20--; CLIMATEMPO, 20--

(created and collected by the author).

Unlike Belo Horizonte, Matozinhos does not have Climate Normals measured by INMET due to the absence of weather stations in the mentioned location. In regards to the main construction systems used in Matozinhos, the tendency addressed in the previous section is also true in the smaller municipality: only 0.06% of households in

Matozinhos are not composed of brickwork or dressed timber (ATLAS BRASIL, 2022). Graph 09 compiles data about this topic in three scenarios to put the values and scales into perspective.

Graph 09: % of households with walls that are not composed of brickwork or dressed timber

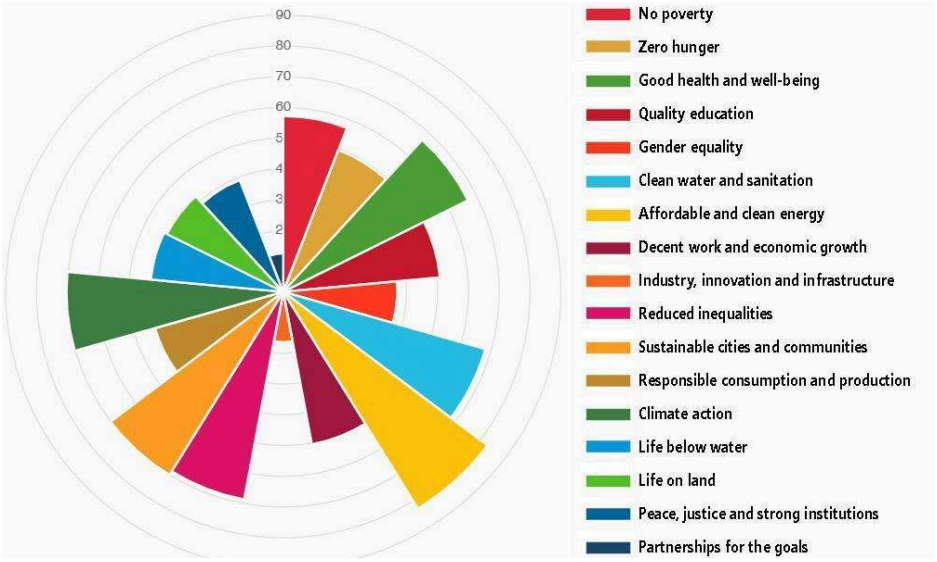


Source: ATLAS BRASIL, 2022. Created by the author.

No information addressing the predominant HVAC systems in buildings in Matozinhos was found up to the present moment. However, in terms of households with access to electricity, the city presented a rate of 100% of coverage according to the latest survey available (ATLAS BRASIL, 2022).

Similarly to Belo Horizonte, Matozinhos has also been searching for ways to accomplish the UN Sustainable Development Goals in its territory (Image 19).

Image 19: Performance per goal in Matozinhos. Data in %.



Source: IDSC, 202-. Adapted by the author.

According to IDSC (202-), the city is ranked in 1275th place among 5570 municipalities (51.08 points in a total of 100). This also puts Matozinhos within a medium level of sustainable development. The goal with the highest index is number 7 (Affordable and clean energy); the second best ranked are goals number 3 (Good health and well-being), 6 (Clean water and sanitation), 10 (Reduced inequalities), 11 (Sustainable cities and communities) and 13 (Climate action). However, the goals with the lowest index are numbers 5 (Gender equality), 9 (Industry, innovation and infrastructure), 16 (Peace, justice and strong institutions) and 17 (Partnerships for the goals) (IDSC, 202-).

A slightly better evaluation than Belo Horizonte in regards to complying to goals number 11 and 13, combined with a good index of goal number 7, hold a promising possibility of improvement of the sustainable practices in Matozinhos. Furthermore, as mentioned in the Urban Energy Planning section, small towns offer less difficulties than consolidated cities when it comes to energy production and are also more flexible to new urban policies, offering an interesting research possibility to study while using CEA as well.

Reducing the scale once again, a portion of downtown Matozinhos was chosen to be simulated. Image 20 illustrates it being outlined by a red contour and a lighter red spot. The reason behind this representation is the same as the one stated in the previous section regarding Belo Horizonte.

Image 20: Section of downtown Matozinhos selected to be simulated on CEA.

Source: CEA. Modified by the author.

Via Google Street View, this section of downtown Matozinhos presents relatively simple buildings from a constructive standpoint, with the majority of them not reaching past three stories - although there are few exceptions (Image 21).

Image 21: Partial view from *downtown Matozinhos*.

Source: Google Street View

Its urban density is massively lower than the one found in downtown Belo Horizonte, but due to its location, downtown Matozinhos also presents a variety of uses in its territory compared to *Céu Azul*, such as single and multifamily residences, commercial buildings such as restaurants, small markets, banks and churches, for instance. The city hall building is also located in this section and it is possible to spot multi-use buildings as well.

The construction standards are less refined than those found in *Lourdes* and it also tracks with the national characteristic of having most of its buildings being built with masonry walls and concrete structures. No survey regarding the presence of HVAC systems in this area was found but, following the same strategy applied in Belo Horizonte, it is possible to notice HVAC systems in the façades of a few buildings via Google Street View. The urban area chosen to be studied and illustrated in Image 20 presented 101 buildings in total, spread in 4 blocks.

2.4.1.4 Comparative Analysis

After delving into some characteristics of both studied cities in terms of their built environment and climate attributes, this section aims to combine these sets of information simultaneously and include Singapore in the equation. The following data, extracted from several sources, are intended to juxtapose Belo Horizonte, Matozinhos and Singapore through a climate and urban-based lens. The main

objective is to further justify the choice of both cities as possible scenarios to apply the same new database, while also highlighting the differences between these two Brazilian cities and the Singaporean context.

Starting off with general information, Table 13 sets the three territories side by side and compares their hierarchy, population and natural traits, such as topography and precipitation. It is possible to notice clear differences between their hierarchies, areas and population: while Belo Horizonte and Matozinhos are both cities and have relatively similar territorial areas, their population sizes are vastly different. This also reflects on the prominently contrasting building density in each city, with Belo Horizonte presenting a higher amount of high-rise buildings. In regards to climate attributes, Belo Horizonte and Matozinhos naturally share more similarities than when compared to Singapore, such as average precipitation and biomes.

Table 13: Comparative approach among Belo Horizonte, Matozinhos and Singapore

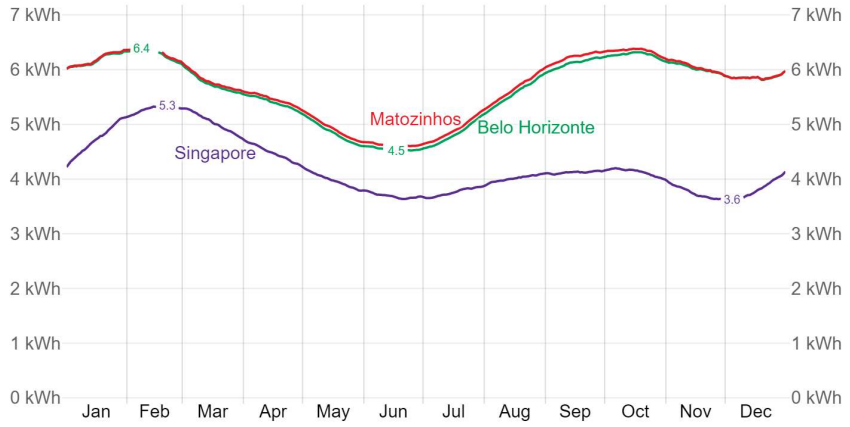
	Belo Horizonte	**Matozinhos**	**Singapore**
Hierarchy	City	City	City-state
Population	Aprox. 2.3 million (2022)	37,618 people (2022)	Around 5 million
Territorial area	331,35 km²	252,45 km²	710 km²
Topography	Variable, with hills and significant slopes in some areas. The average slope is 8.28%.	Variable, presenting plain areas and also hills. Slope values not found.	Most of the territory presents slopes reaching 5.24%, except for central areas where this value go up significantly, some reaching >15%.
Biome	Cerrado (Savannah), Atlantic forest	Cerrado (Savannah)	Tropical rainforest
Climate Köppen-Geiger classification	Mainly Cwa (Humid subtropical climate)	Aw (Tropical savanna climate)	Tropical rainforest (Af)
Average precipitation	1500 mm annually	1400-1601 mm annually	2165,9 mm
Average elevation	895 m above sea level.	600 to 900 m above sea level	Most areas: 1-15 meters above sea level; Central and west regions: 15-55 m; Smaller and dense areas: 55-165 m.

Sources: IBGE, 202-; IBGE, 2020; Weatherspark, 20--; PBH, 2020; Meteorological Service Singapore, 20--; IEDE-FJP, 201-; IPEA, 2015; FERREIRA *et al.*, 2019; MINISTRY OF FOREIGN AFFAIRS, 2023; WANG *et al.*, 2015; NATIONAL PARKS, 2023; JÚNIOR, 2009. Created by the author.

Briefly scaling the climate comparison to a global degree, Belo Horizonte is predominantly ranked within a Cwa climate according to the Köppen-Geiger classification, while Matozinhos falls under the Aw climate (JÚNIOR, 2009). According to the author, the first is described as a humid temperate climate with dry winter and hot summer seasons; the second, on the other hand, is a tropical savanna climate marked with dry winter seasons. As a few examples of locations ranked as Belo Horizonte (KUDACITY, 2019), there are Hanoi, in Vietnam (with around 4.7 mi people), Macau (over 686,000 people) and Shenzhen (around 12 mi), both in China, adding up to over 19 million people in similar climate conditions. As for examples of cities within the same classification as Matozinhos, there are Bangkok, in Thailand (around 10.7 mi people), Brasilia, in Brazil (around 2.8 mi), Caracas, in Venezuela (around 2 mi), Miami, in the U.S. (almost 440,000 people) and Mumbai, in India (21 mi), which encompass over 36 million people.

In terms of incident shortwave solar energy, Belo Horizonte and Matozinhos display considerably close daily values, while Singapore ranks a bit lower in that scenario, according to data from WEATHERSPARK (20--). Such information is relevant to understand the solar energy potential of the studied areas, for instance, and it corroborates the data previously mentioned in the section addressing Belo Horizonte.

Image 22: Average daily incident shortwave solar energy in Singapore, Belo Horizonte and Matozinhos.

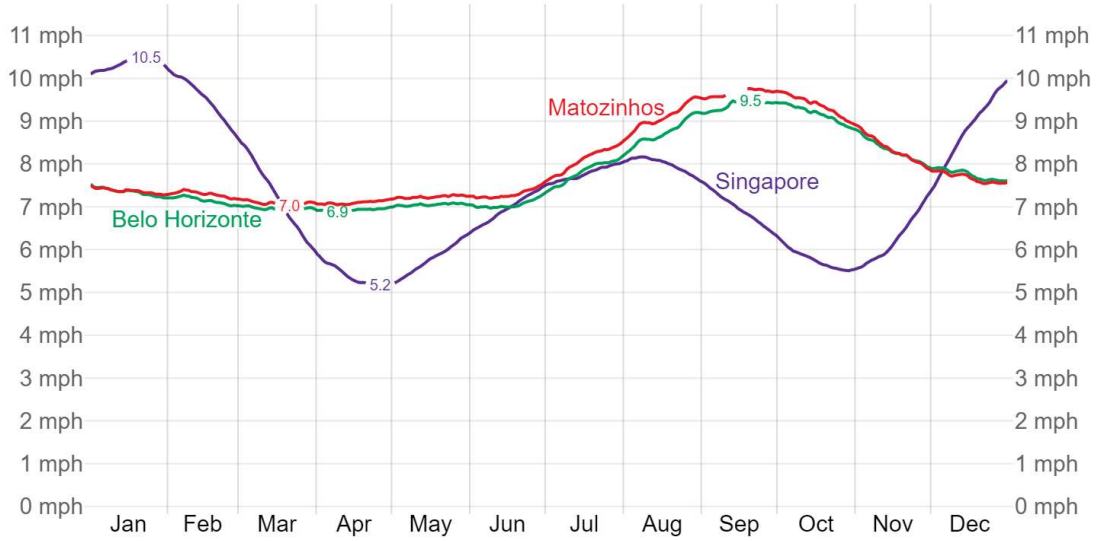


Source: Weatherspark (20--).

In terms of wind speed, once again, the two Brazilian cities present similar values throughout the year according to Image 23, reaching a peak around September. Singapore, on the other hand, displays higher and lower peaks during the year and

reaches its higher average around January. Lower averages tend to appear during April and again in October.

Image 23: Average wind speed in Singapore, Belo Horizonte and Matozinhos.



Source: Weatherspark (20--).

Addressing daylight availability, the Brazilian cities display similar values as expected due to their proximity. However, it is worth noticing that the Singaporean scenario does not diverge too far in this case, presenting close figures to the other two cities.

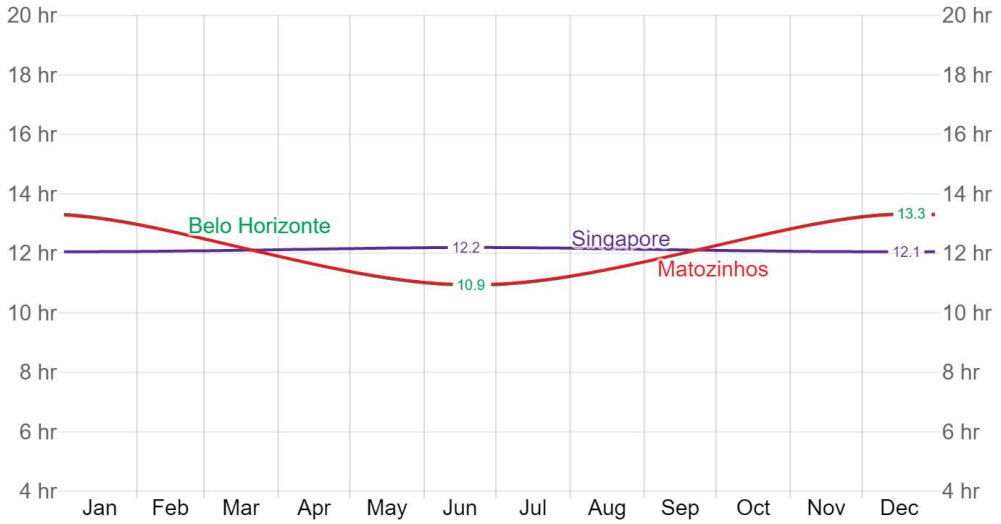
Image 24: Daylight comparison, in hours - Singapore, Belo Horizonte and Matozinhos

Daylight	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Singapore	12.1h	12.1h	12.1h	12.1h	12.2h	12.2h	12.2h	12.2h	12.1h	12.1h	12.1h	12.1h
Belo Horizonte	13.2h	12.7h	12.2h	11.6h	11.2h	10.9h	11.1h	11.5h	12.0h	12.6h	13.1h	13.3h
Matozinhos	13.2h	12.7h	12.2h	11.6h	11.2h	11.0h	11.1h	11.5h	12.0h	12.6h	13.0h	13.3h

Source: Weatherspark (20--).

Image 25 also illustrates the close proximity of all the locations when it comes to annual hours of daylight. Although it is worth mentioning that Singapore displays a more stable value, with less variations according to WEATHERSPARK (20--).

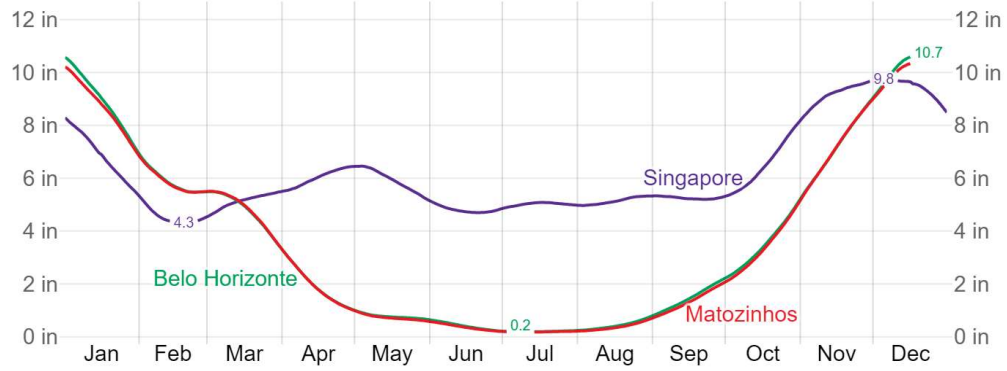
Image 25: Hours of daylight in Singapore, Belo Horizonte and Matozinhos



Source: Weatherspark (20--).

When it comes to precipitation, however, the differences between the Brazilian and Singaporean contexts are visible once again. Image 26 points out that, during most part of the year, Singapore presents higher average monthly rainfall values when compared to Belo Horizonte and Matozinhos. This fact is reversed in the beginning and end of said year. Not surprisingly, the Brazilian cities reach close values in this context as well.

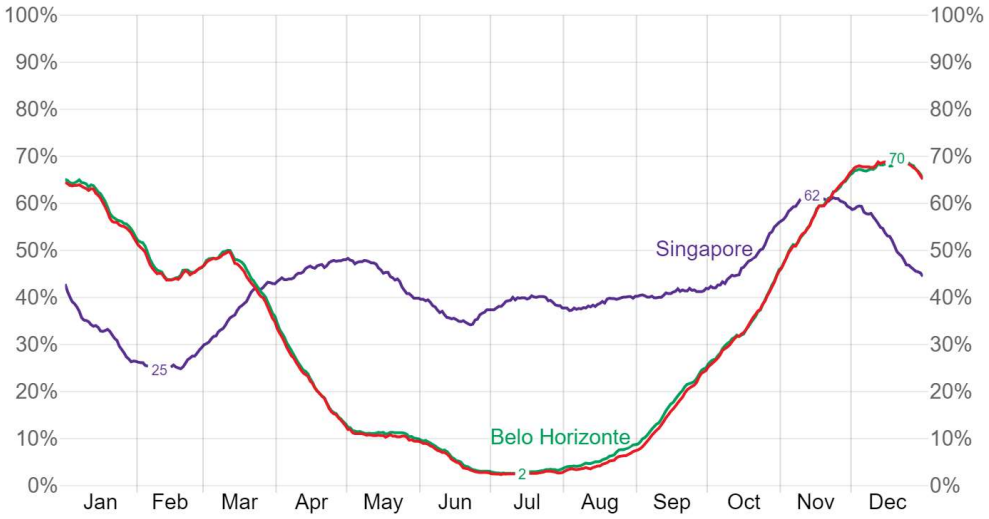
Image 26: Average monthly rainfall in Singapore, Belo Horizonte and Matozinhos.



Source: Weatherspark (20--).

A similar scenario happens when the topic is the daily chance of precipitation in these locations (Image 27), with Singapore reaching higher probabilities of having rainfall than the studied Brazilian cities during the majority of the year.

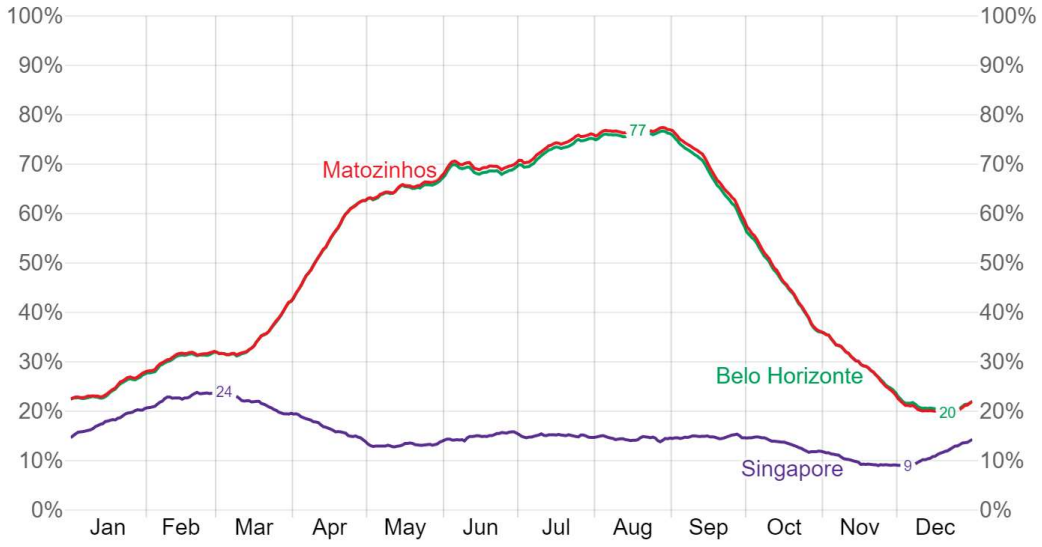
Image 27: Daily chance of precipitation in Singapore, Belo Horizonte and Matozinhos.



Source: Weatherspark (20--).

The situation is reversed when addressing the chances of clearer skies in the three mentioned territories. As shown in Image 28, Belo Horizonte and Matozinhos present 77% of chances for a clear sky as its peak during the year and 20% as their lowest value, while Singapore displays values with a much smaller range (9 to 24%).

Image 28: Chances of clear skies in Singapore, Belo Horizonte and Matozinhos.

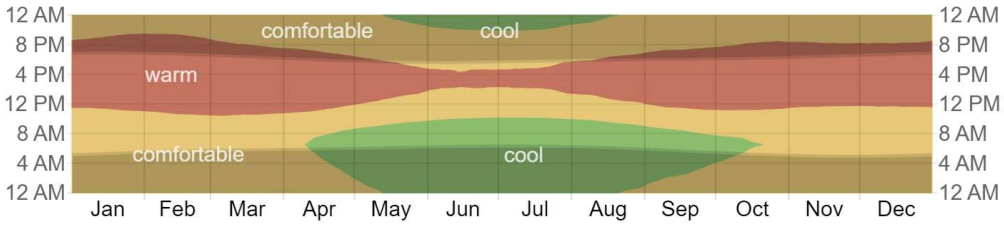


Source: Weatherspark (20--).

Images 29, 30 and 31 allow the comparison of the three locations in terms of their average hourly temperature. While Belo Horizonte and Matozinhos have thermal scenarios going from cool and comfortable to warm, the Singaporean context varies much less frequently and displays a thermal sensation ranging from warm to hot,

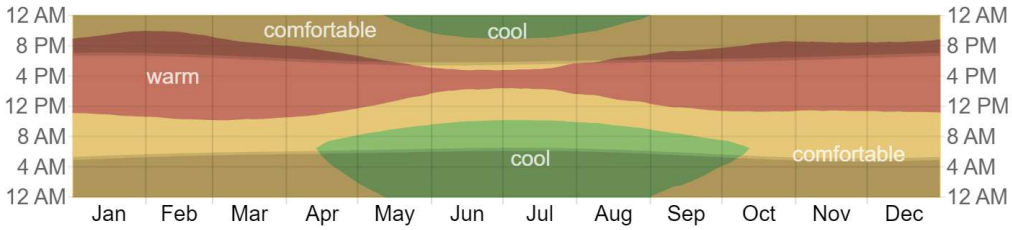
according to data from WEATHERSPARK (20--). The hottest temperatures in Belo Horizonte and Matozinhos tend to appear during the afternoon and at night, mainly from January to May and from August to December. The lowest temperatures in these Brazilian territories are normally found during the morning and at dawn, from April to September/October.

Image 29: Average hourly temperature in Matozinhos.



Source: Weatherspark (20--).

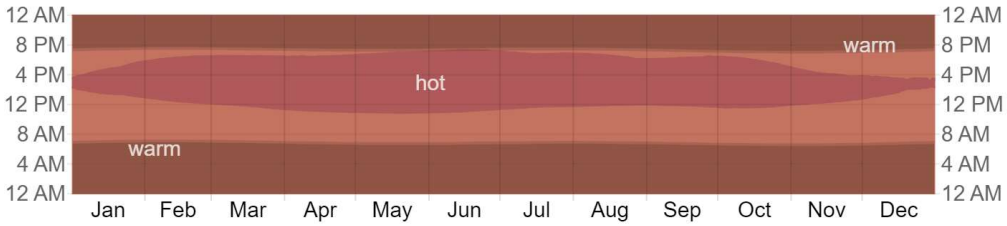
Image 30: Average hourly temperature in Belo Horizonte.



Source: Weatherspark (20--).

In Singapore, as shown in Image 31, the scenarios with higher temperatures are commonly found in the afternoon and later periods, throughout the year. The warm periods, on the other hand, are more often during the morning and at dawn.

Image 31: Average hourly temperature in Singapore.



Source: Weatherspark (20--).

In regards to the highest and lowest temperatures, Image 32 compiles data from the three locations. Singapore presents a more limited temperature variation in both scenarios, while the Brazilian cities tend to reach higher amplitudes. As most of the

world adopts the Metric System, the following temperatures were converted from Fahrenheit to Celsius.

Image 32: Temperatures in Singapore, Belo Horizonte and Matozinhos.

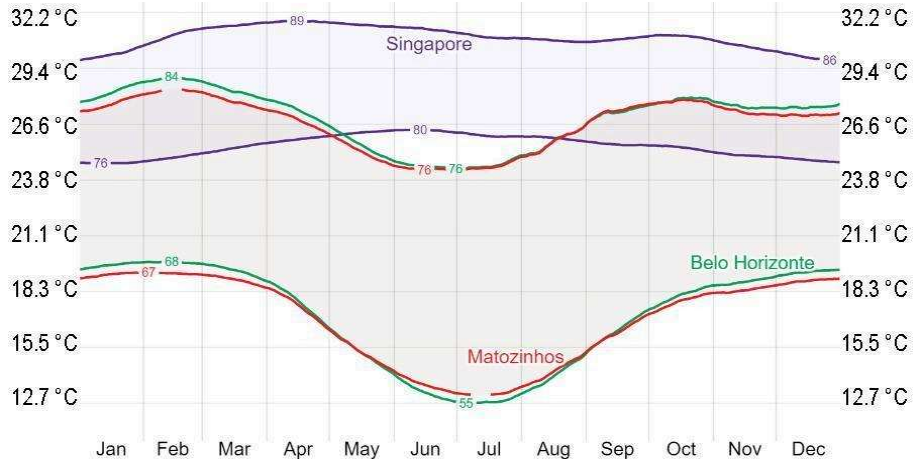
High	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Singapore	30°C	31.1°C	31.6°C	31.6°C	31.6°C	31.1°C	31.1°C	31.1°C	31.1°C	31.1°C	30.5°C	30°C
B. Horizonte	28.3°C	28.8°C	28.3°C	27°C	25.5°C	24.4°C	24.4°C	26°C	27°C	27.7°C	27.7°C	27.7°C
Matozinhos	27.7°C	28.3°C	27.7°C	26.6°C	25°C	24.4°C	24.4°C	25.5°C	27°C	27.7°C	27°C	27°C

Low	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Singapore	25°C	25°C	25.5°C	26°C	26°C	26°C	26°C	26°C	25.5°C	25.5°C	25°C	25°C
B. Horizonte	19.4°C	20°C	19.4°C	17.7°C	15°C	13.3°C	12.7°C	14.4°C	16.6°C	18.3°C	18.8°C	19.4°C
Matozinhos	19.4°C	19.4°C	18.8°C	17.7°C	15°C	13.8°C	13.3°C	14.4°C	16°C	17.7°C	18.3°C	18.8°C

Source: Weatherspark (20--). Adapted by the author.

As the last set of data gathered from WEATHERSPARK (20--), Image 33 illustrates in the form of a graph the average high and low temperatures of all the three locations mentioned previously. Singapore presents more prominent values related to average high temperatures than Belo Horizonte and Matozinhos in a year. The former's lower temperatures are also higher than the values from the Brazilian cities from May to August. However, as an observation, it is relevant to mention the thermal sensation and temperature values are varying considerably due to the impacts caused by the climate crisis the world is collectively facing at the moment.

Image 33: Average high and low temperatures in Singapore, Belo Horizonte and Matozinhos.



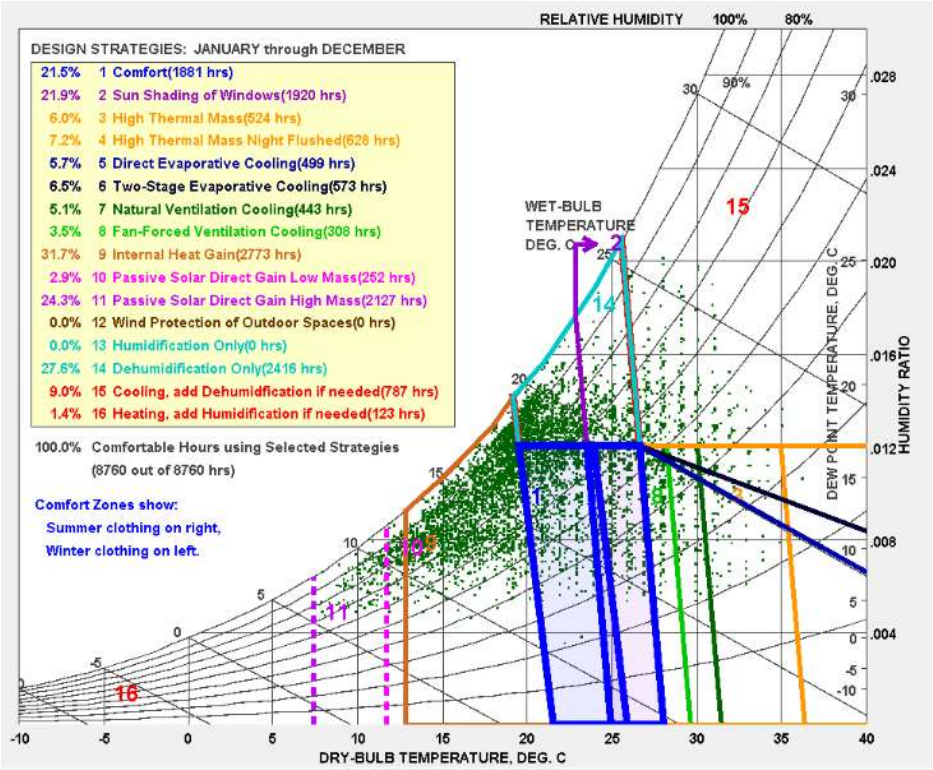
Source: Weatherspark (20--). Adapted by the author.

Going further into the microclimate comparison, two psychrometric charts (Images 34 and 35) were generated by inserting Singapore and Belo Horizonte EPW format

weather files into a Desktop software called Climate Consultant 6.0, available at the Society of Building Science Educators (SBSE) website. The output, among other data, is a chart where a visual description of the local microclimate is offered, as well as suggested strategies in order to ensure thermal comfort for the users during the 8,760 hours of a year. It points out the total hours in which a building would be able to offer thermal comfort to its users in that location and the amount of time they would be in thermal discomfort, suggesting several mainly passive strategies suitable for that microclimate aiming to improve the building thermal performance.

The mentioned analysis made by the software used as parameters the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) 55/2004 and current Handbook of Fundamentals Model, as well as the PMV (Predicted Mean Vote) index. An observation worth mentioning is that no psychrometric chart was generated for Matozinhos due to the lack of a local weather file, as previously stated.

Image 34: Psychrometric chart of Belo Horizonte.

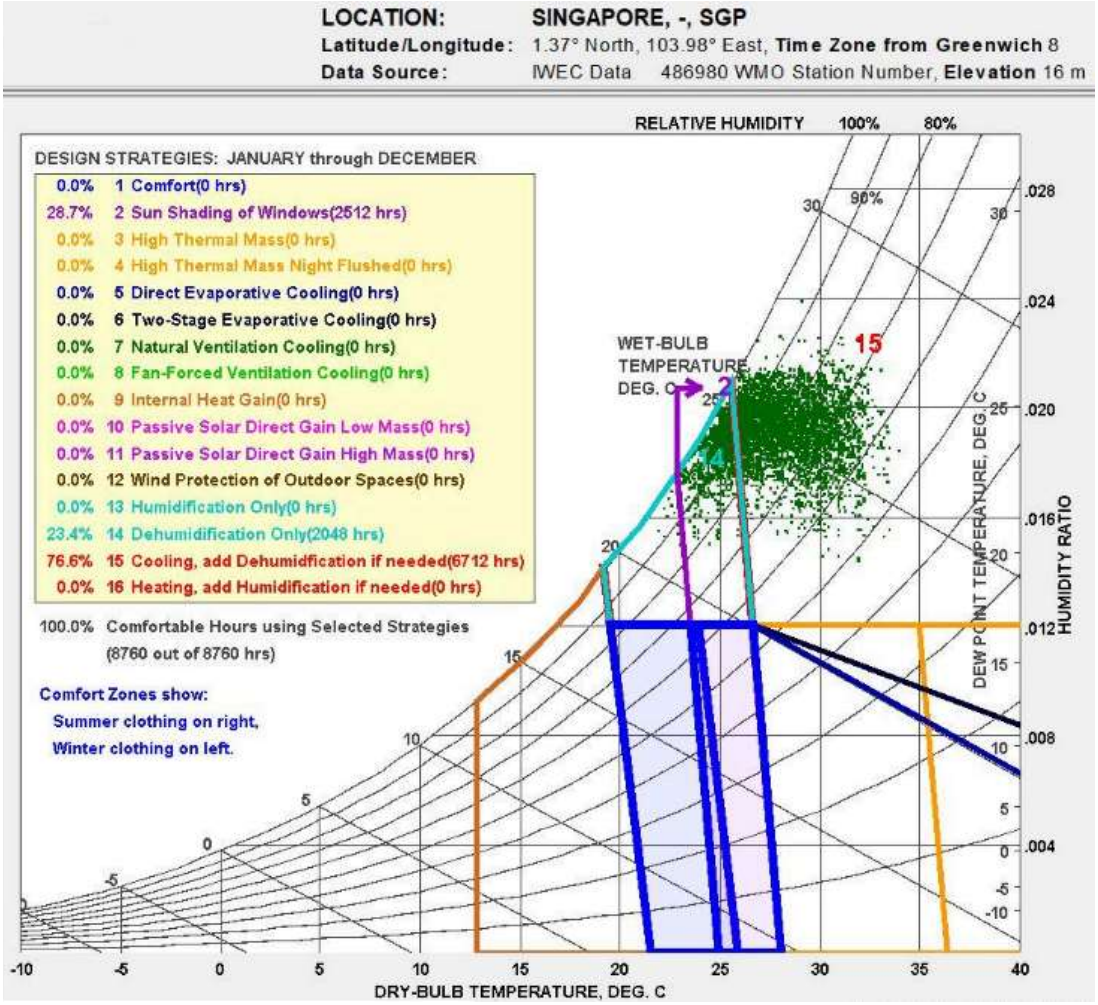


Source: Software Climate Consultant. Created by the author.

Belo Horizonte can offer around 21.5% of the available hours in comfort. The main passive strategies to tackle the discomfort periods are sun shading (21,9%), internal heat gain (31.7%), passive solar direct gain through building elements with high

mass (24.3%) and dehumidification (27.6%). By combining these strategies, it would be possible to reach satisfactory thermal comfort during the whole year.

Image 35: Psychrometric chart of Singapore.



Source: Software Climate Consultant. Created by the author.

Unlike Belo Horizonte, Singapore does not offer thermal comfort naturally, according to the lack of hours in such a state pointed out by the chart. This outcome matches the temperature analysis previously mentioned in this research, where it was possible to notice that Singapore presents hot weather during a large part of the day and the year. The main strategies mentioned to accomplish an improvement in thermal performance and human comfort are sun shading (28.7%), dehumidification only (23.4%) and cooling with dehumidification if necessary (76.6%).

Transitioning to a discussion from a constructive standpoint, additional photos from the three locations were taken using Google Earth so as to visually analyze examples of building typologies and their heights in the studied cities and compare

them. Both downtown and residential areas were considered in each location. These images do not intend to oversimplify the urban characteristics of the studied locations, but rather give a brief example of a reality in each place.

Images 36 and 37: Part of the downtown area (top) and a residential region in Matozinhos, Brazil.

Source: Google Earth.

As the smallest place among the three mentioned locations, Matozinhos presents an urban area with a considerable potential to be further developed. As previously mentioned, part of its central area possesses low-rise buildings as the main representative examples and the building density is lower that Belo Horizonte and Singapore in a similar scenario. Image 37 illustrates an example of a residential area in the city, where similar characteristics can be found: low-rise buildings and low building density. The main building system visually identified is brickwork for the walls, as previously discussed. Image 36 actually depicts part of the chosen area to

be simulated in this research, where it is possible to notice in the background one of the few examples of buildings that surpass the common three-story mark in the city.

Images 38 and 39: Part of Lourdes (top) and Céu Azul (bottom), in Belo Horizonte

Source: Google Earth.

Belo Horizonte, in comparison, presents a much higher building density and consolidated urban fabric. The capital city's lack of space for further expansion could, in a way, be comparable to European realities. Although there is a similarity between them when it comes to the prominent constructive methods and elements, *Lourdes* (Image 38) is predominantly occupied by mid and high-rise buildings, with some areas presenting vegetation and others, surfaces mainly covered by concrete and asphalt. Image 39 illustrates an example of a residential area in the *Céu Azul* neighborhood with predominantly low-rise and single-family buildings. Similar to Matozinhos, these two pictures illustrate parts of the areas to be simulated.

Images 40 and 41: Downtown area and a residential region in Singapore.

Source: Google Earth.

Although in a considerably different economic and environmental context, Singapore displays some characteristics that can be compared to some Brazilian scenarios: downtown area composed of a relevant number of high-rise buildings, paved streets and representative traffic flow. The selected locations in Singapore presented more vegetated areas than the chosen regions in Belo Horizonte and Matozinhos. However, this observation cannot be taken as a rule, since these images represent only a small extract of said places.

The information introduced in this chapter is important to put both Brazilian and Singaporean realities into perspective from an urban standpoint, while also deepening the knowledge in order to create a suitable database for the chosen cities.

3. METHODOLOGY

The methodology adopted for the present research combines elements from both quantitative and qualitative methods, the former being mainly represented by the numerical results gathered from the simulations and the latter complementing it by outlining observations, hypotheses and conclusions based on said results. Due to the nature of this research, a mixed method would enable it to answer its initial questions, such as how applicable CEA would be in a Brazilian context.

In terms of its structure, this research divided its methodology and discussion moments into three phases:

1. **Sensibilization to CEA:** Description of the initial contact with the software, when theoretical and practical approaches to its contents took place and the definition of the first questions to be answered during this initial moment occurred;
2. **Creation of a new database:** The process of understanding the original CEA database and creating the local set of files, named BR, in order to be used during the formal simulations;
3. **Research simulations:** Simulations run with two databases (SG and BR), followed by results comparisons and further discussions about the outcomes, as well as limitations faced in the process.

3.1 Phase 1: Sensibilization to CEA and initial questions

This research stage started off by defining some preliminary questions before getting to know the software in theory and practical terms. They represented the initial sensibilization moment, as a first-time user, to the mentioned digital tool.

- Having in mind that Brazil is a continental-size country with a variety of microclimates, would the program have weather files that could be used to any Brazilian region?
- If so, which climate would better fit in the available database?
- Would it be possible to simulate an entire city or would there be some type of limitations?
- Would there be any need for adaptations in the software for it to encompass the Brazilian urban scenarios?

Following this moment, the CEA official documents were studied in order to fully understand how the software works, which type of data it analyzes during simulations, which possibilities it can offer in an urban scale and if there would be any type of limitation between the digital tool and the Brazilian context. Subsequently, the next step would be to run test simulations using the Singaporean database and a central portion of Belo Horizonte as the case study. Since the initial focus of this part was to understand how CEA works, how it is built, and not gather actual data from the simulations, it is important to highlight that no specific parameters were changed from the default mode before running the simulations. With the combination of both theoretical and practical approaches, the initial questions were answered and deeper possibilities of investigation could be created.

The steps performed for the test simulations are described as follows:

1. A new project was created and named as “BH_test” on CEA;
2. The Singapore file was chosen as the database path option since, as mentioned on the City Energy Analyst documentation released on March 9th, 2023, it would be the most suitable one to tropical climates. The buildings volumetry was obtained directly from OpenStreetMap;
3. Geolocation of Belo Horizonte on the OpenStreetMap was performed. For the purpose of this work, four blocks within the city center were selected as the area to have simulations run on and their immediate surroundings were also included, as it is shown in Images 42 and 43 in black and gray, respectively. A scenario was created;

Images 42 and 43: Top view and 3D of the studied area

Source: CEA, created by the author.

4. As soon as the scenario was created, the available tabs were checked out in order to understand what type of information they compiled. The unavailable ones were put in place by running the scripts on “Tools” > “Data Management”;
5. The following simulations were then run in the following order:
    - Demand forecasting: Building solar radiation, schedules and energy demand;
    - Life Cycle Analysis: Emissions (years of 2000, 2020 and 2030) and System Costs;
    - Energy potentials:Shallow geothermal, water body, photovoltaic-thermal panels, photovoltaic panels, sewage heat and solar collectors.

    The other possibilities of simulation (“Networks” and “Optimization”) were not addressed due to the focus of this work being mainly on the built environment.
6. As soon as all the mentioned simulations were performed, a new dashboard was created where the obtained results could be shown.

Both theoretical and practical approaches were essential to delve into the possibilities the City Energy Analyst could offer to its users.

3.2 Phase 2: Creation of a new database

This phase comprised the entire process of creating the local database for CEA 3.34.2, from describing the analysis of the original files to eventually gathering local information and compiling them in order to create the new local database, named BR. During the creation of the Brazilian database, careful consideration of which variables would or would not apply to the studied areas in Brazil was made. Additionally, limitations found during the process were listed and detailed observations were made. Finally, a complete list with all the sources used as references to feed data into BR was made available at the end of this research.

Two observations are important to be highlighted. First of all, the current version of the BR database is not intended to be applicable to the entirety of Brazil due to a key fact: the timeframe available in this research to have it created combined with the lack of some types of information in Brazil implied in a delimitation of how diverse the database could be, which could mean a future need for expansion in order to cover more data variability. Therefore, the current BR database was originally made for

Belo Horizonte, Matozinhos and any other city with similar energy and urban characteristics.

The second observation to highlight is that the original BR database, created for the 3.34.2 version of the software, was subsequently adapted and generated a second version of it, this time to be used in the newest CEA update (3.37.x). The two versions contain the same data, with the second receiving specific adaptations only to be read by the newest CEA update. After the conclusion of the formal simulations of this research, both BR databases were sent to the software developers at ETH Zürich to go through validation and eventually, if approved, become part of the official set of databases available on the software. The two sets of data will be discussed in this document, with the 3.34.2 version being the focal point due to the fact that it was the one used in the simulations. The 3.37.x version will have its differences from the former database listed.

As a simplified methodology of this phase, it is mentioned the following steps:

1. Investigation of the Singaporean database to catalog each variable included in it and to understand how they are organized. This table is partially shown in Image 44 due to its massive extension (283 lines);

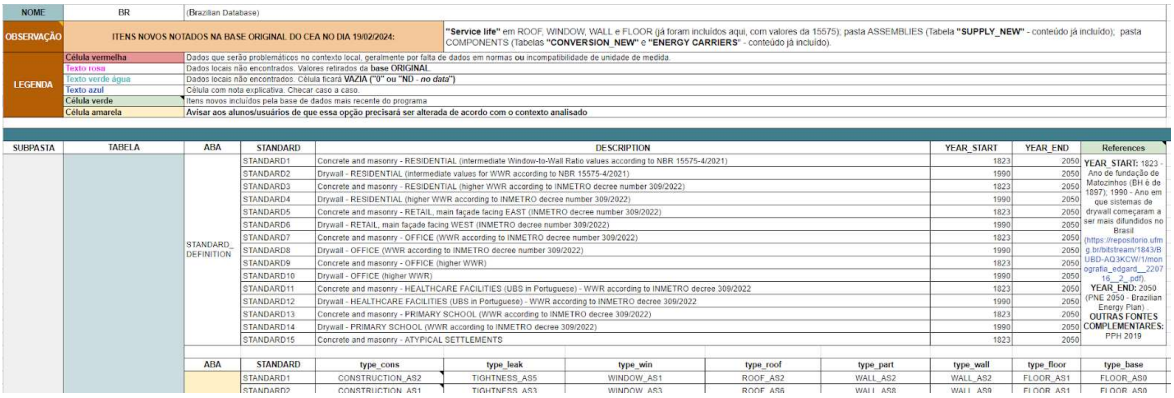
Image 44: Partial view of the table initially created to organize the data from SG (in Portuguese)

ESTRUTURA BÁSICA DA BASE DE DADOS DO CEA						
Pasta da localidade (Ex.: SG) > Pastas principais "Archetypes", "Assemblies" e "Components" **>** Subpastas e/ou arquivos em .csv (Excel)						
OBS. 1: Células em vermelho representam definições de conceitos em que:	Foram encontradas inconsistências na documentação oficial do CEA	OU	Que ainda deixam margem para dúvida.			
OBS. 2: A ISO 13790/2008 foi revisada em 2017 e 2022, sendo a **ISO 52016-1/2017** a vigente internacionalmente no atual momento.						
OBS. 3 - Legenda:	✖	Itens que provavelmente **NÃO** se aplicam ao **contexto da RMBH**				
ATUALIZAÇÃO:	Em pesquisa feita no dia **12/02/2024**, o site **Posses e Hábitos 2019** não estava mais disponível.					
INFORMAÇÕES ABORDADAS NOS ARQUIVOS - Estudo de caso: Database SG (Singapura)						
PASTA PRINCIPAL	**SUBPASTAS / DOCS**	**DADOS APRESENTADOS**				**POSSÍVEIS FONTES** *(Onde buscar por essas informações no Brasil?)*
		Aba "STANDARD DEFINITION"	Nome do padrão (código) - *EX.: CONSTRUCTION_AS1*			N/A
			Descrição (Nomenclatura)	Estrutural e paredes		Principais usados na área estudada: IBGE
				uso da edificação (residential, commercial, etc.)		Principais usos na área (VIDE ABA AO LADO)
				informações específicas	padrão	Por tipologia de edificação
					baixo window-to-wall ratio	
					telhados verdes	
					áreas altamente condicionadas	
					áreas pouco condicionadas	
			Vida útil (Valor numérico)	Ano inicial		Por tipologia de edificação
				Ano final		
		Aba	Nome_padrão			Por edificação (situação real); dados estatísticos sobre a maioria das construções em dada região (IBGE, CENSO, Posses e Hábitos)
			Type_cons (tipo construtivo)			
			Type_leak (estanqueidade ao ar)			
			Type_win (janelas)			
			Type_roof (coberturas/telhados)			
			Type_part (paredes/divisões internas)			
			Type_wall			
			Type_floor (laje de piso)			

Source: Created by the author.

2. Organization of the content gathered in a table. Said table is partially shown in Image 45, once again due to its size (810 lines and over 25 columns);

Image 45: Partial view of the table created to organize data to build BR (in Portuguese)



NOME	BR	(Brazilian Database)	
OBSERVAÇÃO	ITENS NOVOS NOTADOS NA BASE ORIGINAL DO CEA NO DIA 19/02/2024:		**"Service life"** em ROOF, WINDOW, WALL e FLOOR (já foram incluídos aqui, com valores da 15575); pasta ASSEMBLIES (Tabela **"SUPPLY_NEW"** - conteúdo já incluído); pasta COMPONENTS (Tabelas **"CONVERSION_NEW"** e **"ENERGY CARRIERS"** - conteúdo já incluído).
LEGENDA	Célula vermelha	Dados que serão problemáticos no contexto local, geralmente por falta de dados em normas ou incompatibilidade de unidade de medida.	
	Texto rosa	Dados locais não encontrados. Valores retirados da **base ORIGINAL**	
	Texto verde água	Dados locais não encontrados. Célula ficará **VAZIA ("0" ou "ND - *no data*")**	
	Texto azul	Célula com nota explicativa. Checar caso a caso.	
	Célula verde	Itens novos incluídos pela base de dados mais recente do programa	
	Célula amarela	Avisar aos alunos/usuários de que essa opção precisará ser alterada de acordo com o contexto analisado	

SUBPASTA	TABELA	ABA	STANDARD	DESCRIPTION	YEAR_START	YEAR_END	References
		STANDARD_DEFINITION	STANDARD1	Concrete and masonry - RESIDENTIAL (intermediate Window-to-Wall Ratio values according to NBR 15575-4/2021)	1823	2050	YEAR_START: 1823 - Ano de fundação de Matozinhos (BH é de 1897); 1990 - Ano em que sistemas de drywall começaram a ser mais difundidos no Brasil (https://repositorio.ufmg.br/bitstream/1843/BUBD-AQ3KCW/1/monografia_edgard__2207_16__2_.pdf) YEAR_END: 2050 (PNE 2050 - Brazilian Energy Plan) OUTRAS FONTES COMPLEMENTARES: PPH 2019
			STANDARD2	Drywall - RESIDENTIAL (intermediate values for WWR according to NBR 15575-4/2021)	1990	2050	
			STANDARD3	Concrete and masonry - RESIDENTIAL (higher WWR according to INMETRO decree number 309/2022)	1823	2050	
			STANDARD4	Drywall - RESIDENTIAL (higher WWR according to INMETRO decree number 309/2022)	1990	2050	
			STANDARD5	Concrete and masonry - RETAIL, main façade facing EAST (INMETRO decree number 309/2022)	1823	2050	
			STANDARD6	Drywall - RETAIL, main façade facing WEST (INMETRO decree number 309/2022)	1990	2050	
			STANDARD7	Concrete and masonry - OFFICE (WWR according to INMETRO decree number 309/2022)	1823	2050	
			STANDARD8	Drywall - OFFICE (WWR according to INMETRO decree number 309/2022)	1990	2050	
			STANDARD9	Concrete and masonry - OFFICE (higher WWR)	1823	2050	
			STANDARD10	Drywall - OFFICE (higher WWR)	1990	2050	
			STANDARD11	Concrete and masonry - HEALTHCARE FACILITIES (UBS in Portuguese) - WWR according to INMETRO decree 309/2022	1823	2050	
			STANDARD12	Drywall - HEALTHCARE FACILITIES (UBS in Portuguese) - WWR according to INMETRO decree 309/2022	1990	2050	
			STANDARD13	Concrete and masonry - PRIMARY SCHOOL (WWR according to INMETRO decree 309/2022)	1823	2050	
			STANDARD14	Drywall - PRIMARY SCHOOL (WWR according to INMETRO decree 309/2022)	1990	2050	
			STANDARD15	Concrete and masonry - ATYPICAL SETTLEMENTS	1823	2050	

ABA	STANDARD	type_cons	type_leak	type_win	type_roof	type_part	type_wall	type_floor	type_base
	STANDARD1	CONSTRUCTION_AS2	TIGHTNESS_AS5	WINDOW_AS1	ROOF_AS2	WALL_AS2	WALL_AS2	FLOOR_AS1	FLOOR_AS9
	STANDARD2	CONSTRUCTION_AS1	TIGHTNESS_AS3	WINDOW_AS3	ROOF_AS6	WALL_AS8	WALL_AS9	FLOOR_AS1	FLOOR_AS9

Source: Created by the author.

3. Analysis to identify which variables are suitable to the Brazilian context and which are not;
4. Definition of the information needed and research in reliable sources to gather the necessary data. In this step, three possible scenarios were outlined:
    a. Best case scenario: use of national regulations and local documents whenever available (for example, NBRs - *Normas Brasileiras* or Brazilian Standards);
    b. Second scenario: when local documents were not found or did not exist in a specific context, international regulations were adopted (for example, ASHRAE standards);
    c. Worst case scenario: when neither of the first two were available, the specific variable was either taken from the original SG database, defined by an “educated guess” (as it is often done in the SG database itself) or left with generic values followed by explanatory notes.
5. Data compilation and creation of the local database in the same format the original files are presented.

The analysis conducted to understand the original database culminated in the conclusion that specific variables would not be as suitable to the chosen cities (Belo Horizonte and Matozinhos) as they are to Singapore and, therefore, would not be part of the new database, as shown in Table 14. Certain data that would need adaptation are also included. Each one of them, as well as the reason for their exclusion, are mentioned in the same table.

Table 14: Variables excluded or adapted in the new database and reasoning behind the decisions

Excluded or adapted variables	Reasons
Any variable related to a **district scale**	This concept is not commonly used in Brazil. The only two scales addressed in the BR database, more specifically in the tables dealing with supply systems, are “building” and “city”.
Any variable that dealt with air-conditioning systems meant for **heating**	Heating systems are not common in the chosen cities due to its predominantly hot weather. This strategy can be found in upper class buildings. Cooling systems were kept in the database.
Any variables dealing with **hot water for HVAC systems**	Not applicable to the systems commonly found in the studied areas. The cooling systems considered in the simulations (split and window) do not use hot water for cooling.
“Thermal grid”, on the DISTRIBUTION file	It was not excluded because the software would identify it as an error. Instead, since it is not representative or common in the studied scenarios, all the values were set as “1” and an explanatory note for this strategy was inserted in the table.
The following schedules on the “Use_Types” folder: ● Cool room; ● Foodstore; ● Gym; ● Hospital; ● Industrial; ● Lab; ● Library; ● Museum; ● Parking; ● School; ● Server room; ● Swimming; ● University.	The schedules for the BR database were based on national regulations. In these documents, the aforementioned uses were not present, so the database focused on the prominent uses in the two studied areas. Most of them could be substituted by the “retail” schedules. Others, like “Hospital”, “Foodstore” and “School”/ “University”, were substituted by schedules that could fit common Brazilian health units (UBS), markets and primary schools. As mentioned before, the available time frame of this research impacted on how diverse the new database could be.
The following options in the “Conversion” table: ● Furnace; ● Fuel Cell (FC); ● Combined Cycle Gas Turbine (CCGT); ● Borehole (BH); ● Chiller_configuration; ● Heat pump; ● Thermal energy storage.	Options not considered representative or common in the scenarios selected to be studied. Future expansions of the BR database, in order for it to cover larger areas of Brazil, might eventually include them if these strategies become representative in the country.
The following variables in the “Feedstocks” tab: ● Original notion of “grid” *;	● *Adaptation on the GRID tab: Adapted. The original notion of grid is not the same in the SG

• Biogas; • Natural gas; • Oil; • Coal; • Wood; • Wet biomass; • Dry biomass.	and BR databases. In the Brazilian case, it represents the SIN (National Interconnected System or *Sistema Interligado Nacional*, in Portuguese), being represented by several energy sources, such as hydropower plants. The name was originally changed from GRID to SIN. However, the software read it as an error, so the original name was kept. The data, however, was collected from SIN; • Biogas, oil, coal, wood, wet biomass and dry biomass: Excluded. Not relevant in the studied area when it comes to the electricity matrix. Oil is representative in the energy matrix; • Natural gas: Excluded. Not as representative in the Brazilian context, even though it has indeed presented an increase in recent years, as mentioned in the energy section. However, in terms of the electricity matrix, it is not used in the studied areas. Natural gas, alongside wood and LPG, are mainly used for cooking purposes in Brazil and, for that use, CEA does not offer an option to insert this type of information. In fact, the units used in the "Feedstocks" table are not comparable to such uses, since they consider kWh (kilowatt hour). This can be considered a drawback in terms of using the software in a Brazilian context, since LPG is a relevant item for the residential sector.
Data related to **emissions**	Incompatibility of units between software ($KgCO2/m^2$) and local documents researched ($kgCO2eq$).

Source: Created by the author.

These alterations, as well as other relevant observations made during the creation of the BR database, are further addressed in the discussions chapter.

In terms of the construction and occupation information to be added into the new database, Table 15 follows the same logic as the previous one and summarizes the preliminary data for this topic, as well as the reasoning behind it. For more details, it is recommended direct access to the BR database itself.

Table 15: Summary of uses, construction and HVAC data to be added in the BR database

Included information			Reasons
SCHEDULES	The following uses received a specific schedule: • Single-family building; • Multi-family building; • Commercial/Retail; • Office; • Primary school; • Basic healthcare units; • Hotel; • Market; • Restaurant.		The most frequently found uses in the areas to be studied, with some of the most representative values when it comes to energy demand, for instance. Additionally, they were the options offered by the national regulations used to gather data from, such as INI-R and INI-C (energy efficiency evaluation methods for residential and commercial/public buildings, respectively).
CONSTRUCTION	**Wall systems**	**External walls:** • Ceramic bricks • Concrete blocks • Drywall with cement panels	Most prominent elements and systems used by the Brazilian building industry. When it comes to atypical settlements (those which are built without technical orientation or legal permission), they are also found with a relevant frequency. The database also details internal and external coating when it comes to walls, for instance.
		Internal walls: • Ceramic bricks • Concrete blocks • Drywall with plasterboards	
	Roof systems	• Concrete flat slab • Ceramic roof tiles • Metal roofing sheets • Insulated roof panels	
	Floor systems	• Internal concrete floor	
	Windows elements	• Wood frames, single colorless glass; • PVC frames, single colorless glass; • Aluminum frames, single glass; • Glazed façades, Low-E double glass; • Laminated gray glazed façades; • Laminated blue glazed façades; • Reflective gray glazed façades.	Most prominent options in the studied areas. Additional options that were not found in the studied areas were also added in order to increase the database variability.
	Shading devices	• Horizontal blinds (internal); • Vertical blinds (internal); • Curtain (internal); • Horizontal brise soleil; • Vertical brise soleil; • Eave (*beiral*); • Marquee (*marquise*);	Common elements found in Brazilian buildings, some more frequent than others depending on the building construction standards and the region where it is located.
	Construction	• Light construction; • Medium construction; • Heavy construction.	Values taken from a draft standard being discussed in Brazil. No official regulations

			were found.
	Tightness	Values taken directly from the SG database (from 1 - highly tight - to 6 - very leaky).	Lack of national regulations defining such values.
HVAC SYSTEMS	**Cooling**	• Window air conditioning system ("*Janela*"); • Split air conditioning system (Hi-wall / High Wall) • Split air conditioning system (Cassette); • Central air conditioning system	Most common types of air-conditioning equipment found in the studied areas. Note: central systems were not used in any of the simulations run.
	Heating	Not applicable	Heating systems are not being considered in the studied areas.

Source: Created by the author.

To create the local database, the aspects analyzed in each city needed to be similar to those present in the original CEA database, as the idea is that the new set of information would follow a corresponding pattern as the original files, but with data from Brazilian scenarios feeding it instead. As summarized by Table 15, some of the characteristics observed encompasses predominant constructive methods, relevant building cooling systems adopted in the studied areas, the variety of building uses and its occupancy patterns, among others detailed in the BR database itself.

However, local scenarios did interfere with the chosen variables to be applied in said database, as pointed out by Table 14. The reasons for such decisions are the existence of contrasts between Brazil and Singapore when it comes to aspects such as predominant HVAC systems, urban fabric and main energy sources, for instance; as well as some limitations found within the software when it comes to answer specific local questions, as it will be pointed out in the discussion chapter. Another pertinent difference to be highlighted is the concept of districts, not used in the Brazilian scenarios. Due to the latter, the only two scales included in the Brazilian database - more specifically, in the tables dealing with supply systems - were "building" and "city".

Once the beta version of the BR database was ready, the next phase could begin with the process of running the formal simulations within the chosen urban sections in Belo Horizonte and Matozinhos.

3.3 Phase 3: Research simulations

In this section, the methodology for the set of simulations with both the original (SG) and local database (BR) is described. The step-by-step will be relatively similar to Phase 01, but now including the areas within Belo Horizonte and Matozinhos. Before approaching the process itself, it is relevant to highlight four main points that differ this phase from the first one:

- The areas within the cities were not defined by the concept of “districts”, as the original databases do, but by “city blocks” - an easily understandable concept in which the areas are clearly delimited as well. Additionally to that, due to the massive amount of data to be set for individual buildings in each scenario and the available time frame for this Master’s research, the range of buildings to be simulated was set to vary between 90 and 120 units in each area;
- The three areas were chosen due to an additional range of different characteristics among each other that could help generate a variety of results simultaneously to be discussed in this research. These differences are:

Image 46: From left to right, BH1, BH2 and MTZ1.

Source: CEA. Modified by the author.

  - Lourdes/ Belo Horizonte (code used: BH1): Considerably high urban density, near downtown and with high-rise buildings (some of them with mixed use) in its territory. Mid and high standard constructions with multiple uses and full access to urban infrastructure. An area considered to be part of what is called “formal city” (*cidade formal*, in Portuguese), where, in other words, the majority of buildings were built with technical guidance and complying to local legislations (GHIONE, 2013). In terms of data availability, this section is located in a city with a

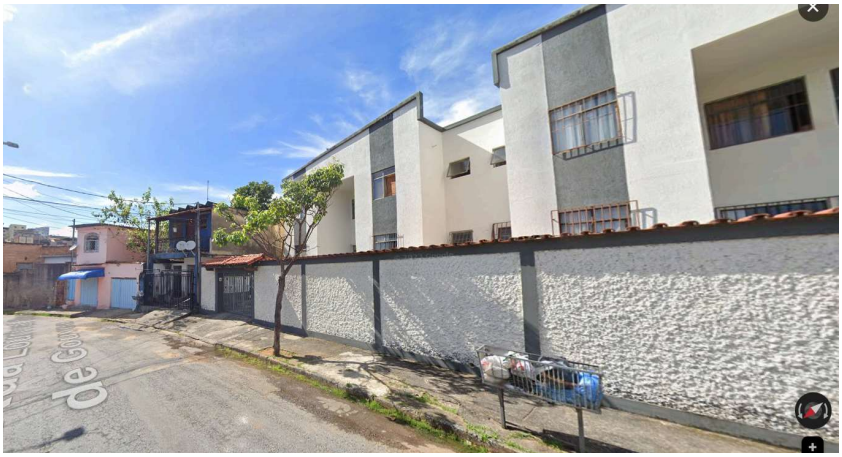
high quantity of available information provided by, among other sources, local authorities (example: BHMap website). BH1 was already modeled on OpenStreetMap before the simulation process began;

Image 47: Examples of buildings in BH1

Source: Google Street View.

- *Céu Azul* / Belo Horizonte (code used: BH2): Lower urban density, distant from the downtown area and predominantly occupied by low-rise residential buildings, with smaller commercial points still present. Population with a lower income when compared to BH1, but still with access to urban infrastructure nonetheless. In the area, it is possible to see examples of buildings linked to the concept of “informal city” or, in this specific research, “atypical settlements”: buildings that were most likely built without technical guidance nor compliance to local construction codes. Access to information is still higher than the next area to be addressed due to BH2 being part of Belo Horizonte as well. However, unlike BH1, this area was not available on OpenStreetMap and, therefore, had to be manually modeled for the simulations;

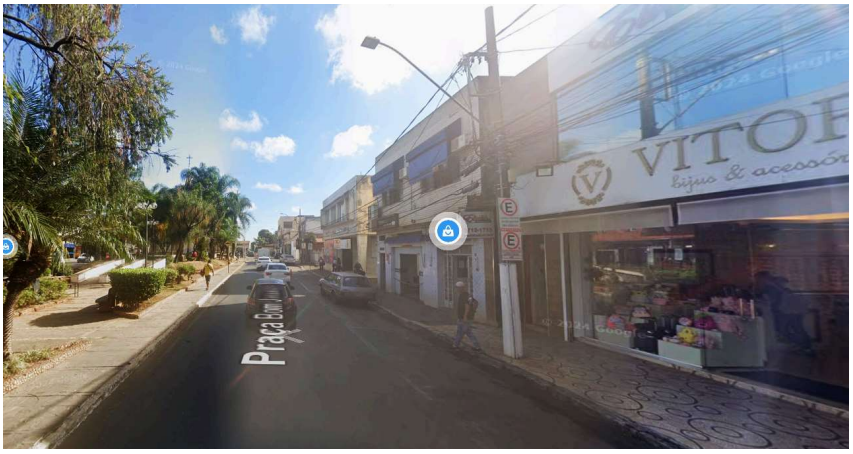
Image 48: Examples of buildings in BH2



Source: Google Street View.

- Downtown Matozinhos (code used: MTZ1): High urban density due to it being a central area in the city with multiple uses in its territory. Urban infrastructure is visible, but buildings reach lower heights in the majority of cases (1 to 3 floors, with a few exceptions). Area located in a city with a considerable lack of data. Similar to BH2, MTZ1 had to be modeled from scratch as well.

Image 49: Examples of buildings in MTZ1



Source: Google Street View.

- The areas that were not available on OpenStreetMap prior to the simulations were manually modeled to enable the beginning of Phase 3. This modeling task involved using the free OpenStreetMap platform to define 3D shapes, building heights, number of floors and uses in both areas. It was performed by the undergraduate students that participated in the first CEA module offered

by the author of the present work and her Master's supervisor at UFMG School of Architecture from March to May, 2024. This module was an additional research development and is fully detailed in chapter 5;

- Unlike Phase 1, the results are taken into consideration in Phase 3 in order to compare the outcomes obtained between the SG and BR databases.

The formal simulations had the following information defined, which are further detailed in the discussions chapter:

1. Definitions of the three areas to be simulated on CEA (BH1, BH2 and MTZ1), all of them available in 3D on OpenStreetMap by this point;
2. Selection of weather files (.epw), with data from 2007 to 2021, for each area:
    a. BH1: "Belo Horizonte - Carlos Prates";
    b. BH2: "Belo Horizonte - Pampulha";
    c. MTZ1: "Belo Horizonte - Carlos Prates" (Note: Matozinhos does not possess its own weather file and the Carlos Prates version is suitable for urbanized areas).
3. Selection of the CEA databases to be used: SG (original) and BR (new);
4. Input settings:
    a. Data to be defined on the "Tools" button:
        i. Data Management: all scripts - Mandatory scripts;
        ii. Demand forecasting: building solar radiation, building schedules and energy demand - Mandatory scripts in order to have access to the simulations run in the Energy Potentials tab;
        iii. Energy Potentials option: Photovoltaic (PV) panels; Photovoltaic-thermal (PVT) panels and solar collectors (evacuated-tube) - The technologies chosen to be simulated in this tab were defined as being the most prominent out of all the other options in the studied areas.
    b. Data to be defined in the 09 tables on the "Input Editor" button:
        i. Zone;
        ii. Typology;
        iii. Architecture;
        iv. Internal loads;
        v. Indoor comfort;

vi. Air-conditioning systems;
vii. Supply systems;
viii. Surroundings;
ix. Schedules.

All of them are necessary tabs to be configured in order to run the simulations. Due to the large number of buildings studied, it was prioritized that the input configuration would be done with a higher level of details in the most representative buildings, as the discussion chapter points out. From each area, a number of specific buildings were analyzed in detail and had their results compared between the SG and BR databases.

c. Buildings to be analyzed in details in each of the three studied sections:

i. BH1 (*Lourdes*), 08 buildings:
   1. B1000 (set as SINGLE_RES with HVAC systems using the SG database and without air-conditioning systems using the BR database);
   2. B1002 (set as HOSPITAL with the SG database and HEALTH_UBS with the BR database);
   3. B1003 (set as RETAIL with HVAC systems in both cases);
   4. B1004 (set as OFFICE with HVAC systems in both sets);
   5. B1005 (set as RESTAURANT in both cases);
   6. B1007 (set as MULTI_RES with HVAC systems),
   7. B1021 (set as SINGLE_RES with HVAC systems);
   8. B1067 (multi-use building set mainly as OFFICE and secondly RETAIL, with HVAC systems, in both cases).

ii. BH2 (*Céu Azul*), 05 buildings:
   1. B1000 (set as SINGLE_RES without HVAC systems using both databases);
   2. B1040 (set as SINGLE_RES with HVAC systems);
   3. B1050 (set as RETAIL with HVAC systems);
   4. B1067 (set as MULTI_RES without HVAC systems);
   5. B1072 (set as SINGLE_RES without HVAC systems using both databases). With the BR database, this building was

defined as an “atypical settlement” based on a visual analysis of its construction standards and finishing level.

iii. MTZ1 (Downtown Matozinhos), 06 buildings:

1. B1000 (real-life supermarket set as MARKET with HVAC systems using both databases);
2. B1013 (set as SINGLE_RES without HVAC systems);
3. B1022 (set as MULTI_RES/RETAIL with HVAC systems);
4. B1062 (set as OFFICE without HVAC systems);
5. B1090 (real-life church set as SCHOOL with the SG database and PR_SCHOOL with the BR one, both without HVAC systems);
6. B1095 (set as RETAIL with HVAC system). Use adapted to the available schedules in the databases.

5. Results to be collected:

The variables chosen to be analyzed in all studied areas are listed below. It is important to highlight that other variables were simulated as well, but only the following were selected to be the final output due to their relevance for the studied areas, especially when it comes to the Energy Potentials tab.

ENERGY DEMAND

a. Comfort charts (generated for each building individually) - Objective: Analyze the interaction between weather files and databases;
b. Energy balance (same as above) - Objective: Pinpoint the highest gains and losses of each building chosen, also considering their use, construction characteristics and artificial cooling, when applicable;
c. End-use and end-use intensity (generated for the whole area) - Objective: Analyze the main uses where the energy was destined to and how predominant they were in each building;
d. Energy final use and final use intensity (whole area) - Same reasoning as above.

SOLAR POTENTIALS

a. Solar radiation (normalized by surface area, monthly) - Objective: Combine this information with the energy potentials to study possibilities with each building.

ENERGY POTENTIALS

a. Photovoltaic (PV) potential - Normalized by surface area, monthly;
b. Photovoltaic-thermal (PVT) potential;
c. Solar collector (evacuated tube) potential - Normalized by surface area, monthly.
d. Objective: Study the most relevant technologies within the studied areas.

In the “Solar Potentials” and “Energy Potentials” tabs, only roofs were considered for the analysis due to it being the most prominent surfaces in which equipment such as PVs would be installed. Additionally, the reason to choose “surface area” as the normalization standard was because it was understood that “surface area” meant the surfaces in which the incident radiation would reach (in this case, only the roofs). These variables and the logic behind them were the same for all three areas.

Following a similar logic as Phase 1, the step-by-step process applied in Phase 3 can be summarized as follows and was repeated for each one of the scenarios created:

1. A new project was created and named as “OFFICIAL_SIMUL” on CEA;
2. Each area had two versions of scenarios created within this project: one for the SG database and the other, for the BR one. Therefore, in total there were 06 scenarios to be analyzed and compared. They were named as follows: BH1_SG; BH1_BR; BH2_SG; BH2_BR; MTZ1_SG and MTZ1_BR. The initial definitions for each scenario are exposed in the discussion chapter;
3. Each area was delimited on the OpenStreetMap tool available on CEA, creating all the 06 scenarios mentioned;
4. As soon as each scenario was created, the input data was set in both “Tools” and “Input Editor” buttons. The configuration chosen for each area is detailed in the next chapter as well;
5. All the simulations mentioned in Item 4 in the previous paragraph (“Input settings”) were performed with each of the 06 scenarios;
6. As soon as all the simulations were performed, a new dashboard was created for each scenario and the collected results were shown;
7. Each pair of scenarios was compared to each other (BH1_SG and BH1_BR, for instance). Some additional aspects were considered in this process, such

as the level of similarity or dissimilarity in the results from both databases, the existence of any incompatibility or unexpected results in the simulations, the response the software offered to the local questions and its level of sensibility to atypical settlements.

With the three phases defined and the BR database completed, the works proceeded and each of their findings, as well as limitations, are listed in chapter 4 (Discussions). The numerical results helped answer the guiding questions and also formulate further discussions and suggestions regarding the software and database, as it is addressed in chapter 6 (Conclusions). This characteristic, once again, highlights the relevance of the present methodology to be a combination between quantitative and qualitative approaches.

Additionally, the phases defined in the present chapter were crucial to not only answer the level of application CEA currently offers to Brazilian scenarios, but also enable a critical and deep analysis of both the software and its databases when it comes to answering questions that are considerably common in developing nations such as Brazil. Thoughts on the BR database are pointed out in the next chapter. The undergraduate module that originated from the present research is detailed in chapter 5 (Additional Research Developments) and, lastly, final observations, software suggestions and potential investigation topics for future works are addressed in chapter 6.

4. DISCUSSIONS

This chapter will focus on discussing in detail the three phases the methodology addressed, as well as possibilities of the software, its strengths and limitations in Brazilian contexts. Each phase answers different questions and, collectively, they support the conclusions of the final chapter.

4.1 Phase 1: Initial sensibilization with existing database

Phase 1 focused on understanding how the software and its database worked. The main goal of performing simulations using Belo Horizonte as a case study was not to gather data, but rather understand the intricacies, strengths and eventual limitations of CEA, as well as recognizing how it could be used or adapted to Brazilian urban planning.

This phase was guided by the initial questions mentioned in the previous chapter. However, it is worth emphasizing that these inquiries were defined before the first contact with CEA. Phase 1 helped not only answer those questions, but correct some assumptions made about the types of information the databases contained, as well as how the software was structured.

Combining the mentioned information with some observations made during the process, it is possible to conclude the following:

- Having in mind that Brazil is a continental-size country with a variety of microclimates, would the program have weather files that could be used to any Brazilian region? If so, which climate would better fit in the available database?
    - CEA works with two main types of databases: weather files that can be downloaded from websites like Climate.OneBuilding.Org and its original databases (in the 3.34.2 version, CH and SG). In regards to the weather files, there is a vast variety of them online, including from hundreds of Brazilian cities. Therefore, through this point of view, the climate characterization would not be a limitation. However, the original databases in the mentioned CEA version are much more limited, having only one option destined to tropical regions: the SG database, used in the present research. These original files comprise data ranging from construction techniques, thermal comfort information, HVAC systems,

electricity supply systems, occupation schedules, among others that can vary drastically from country to country depending on their urban, construction and energy realities, for instance. Therefore, having a database with local information, common systems used in the country and occupation schedules that fit the local reality and regulations would be beneficial to gather more precise results in simulations.

- Would it be possible to simulate an entire city or would there be some type of limitations?
    - The software is noticeably detailed in regards to construction and HVAC systems, displaying each building in the studied area along with its use, energy demands, occupancy schedules, construction materials, among other relevant variables. Due to the time limit and amount of variables to be analyzed, the present research focused on limiting the studied area to 90-120 buildings, choosing urban regions that could potentially offer interesting possibilities for comparisons. Nonetheless, it was noticed that CEA can simulate hundreds of buildings simultaneously as long as the area is limited to 100 km², which would naturally require more computer processing power proportionally to the vastness of the chosen area.
- Would there be any need for adaptations in the software for it to encompass the Brazilian urban scenarios?
    - This topic is discussed in detail from Phase 2 onwards.

Other initial observations were drawn during this phase, also being made in the very beginning of understanding the software:

- Initially, it was noted that not every area in the city had a 3D geometry available at OpenStreetMap, which would in theory prevent the simulations to be run at all or the results to be precise. However, with information gathered during the theoretical part, it was understood that CEA offered two possibilities in this regard: uploading a shapefile with the intended area to be studied or using the free OpenStreetMap platform to model the missing area, which would eventually make it visible on CEA due to the connection between the platform and the software;

- During the initial simulations, it was noticed that even when a building is manually defined as having multiple uses (residential and retail, for instance), the schedules tab only displays one table to define such parameters. Taking the specificities between the two uses into account, a new hypothesis was drawn about this potentially being a factor that could influence the simulations. As an example, the occupation difference in peak hours between residential and commercial uses would cause a variation on the energy demands results. Further investigation was conducted and a scenario was created where one of the buildings was set as having 50% of its gross floor area occupied by retail spaces (RETAIL) and the other 50%, by a single-family residence (SINGLE_RES), while another building was set to have 80% of its area defined as multi-family apartments (MULTI_RES) and the remaining 20%, retail spaces (RETAIL). A trial simulation was run and it was shown that the software would only consider the schedule from the first use in both cases. This is explained by the fact that CEA defines the “1st Use” as the main use of the building. Although this initial investigation was answered, this outcome still raises questions in terms of the results accuracy since the second use is apparently ignored by the software;
- Having the possibility of comparing two different scenarios when it comes to emissions (baseline vs. 2050, for example) is particularly compelling, as it is universally clear that, from the last few years and going forward, one of the focal points is and will be helping rethink current ways of planning in order to reach carbon-neutral buildings and cities;
- The renewable Energy Potentials panel displays some energy sources that are a reality in Brazil, such as solar collectors and photovoltaic panels, which is a relevant feature in order to run simulations within the Brazilian context.

The observations drawn have assisted this research to initially grasp the possibilities offered by CEA and how Brazil could eventually be benefited from it.

4.2 Phase 2: Investigation of the original database and creation of BR

Phase 2 was focused on working through the SG database to understand how it is built and what type of information would be needed in order to create the Brazilian database. It was imperative to understand which types of information the database would need to address, as well as identifying those that would be suitable to a Brazilian context, those that would not and the type of information that would need adaptation. As mentioned previously, an Excel table was created and every variable from every single table was identified, listed and grouped for further studies. Those that did not fit the studied cities' context were identified and flagged in the list. Potential sources of information were mentioned.

The process briefly described in the methodology chapter in regards to Phase 2 is further detailed in the following sections.

4.2.1 Investigation of the Singaporean database and observations

To briefly recapitulate, the main content of the original SG database folder of CEA version 3.34.2 is structured as follows:

- “ARCHETYPES” folder: Composed by an Excel file named “CONSTRUCTION_STANDARD” and another folder (“USE_TYPES”), where another Excel file (“USE_TYPE_PROPERTIES”) and additional 19 .csv files are contained with the schedules of each of the uses available: Foodstore, Gym, Hospital, Hotel, Industrial, Lab, Library, Multi-family residences, Museum, Office, Parking, Restaurant, Retail, School, Server room, Coolroom, Single-family residences, Swimming and University. There is also a .txt file with notes regarding source references for some data;
- “ASSEMBLIES” folder: 04 Excel tables named “ENVELOPE”, “HVAC”, “SUPPLY” and “SUPPLY_NEW”, the latter being a table with updated information from the last CEA version for the Singaporean reality. In the BR database, “SUPPLY_NEW” would basically be a copy of the original file due to the fact that this is the first version of the Brazilian database. Therefore, there would be nothing to update;
- “COMPONENTS” folder: 05 Excel tables named “CONVERSION”, “CONVERSION_NEW” (same logic as the previous folder), “DISTRIBUTION”, “ENERGY_CARRIERS” and “FEEDSTOCKS”.

In summary, it was noted that the first mentioned folder contained mainly the default options from the database that would appear on CEA (and that can be changed in each building by the user directly on the software), occupation schedules for each available use and data related to internal loads and indoor comfort. The second provides options to characterize each building in terms of its envelope (wall systems, roof systems, shading devices, windows, floor systems, construction tightness and how light or heavy the construction standard is considered to be), HVAC systems (cooling, heating and hot water) and supply systems for HVAC equipment and electricity. Lastly, the third folder details more options of supply systems, energy sources (grid, solar, natural gas, wood, etc.), a collection of equipment such as air-conditioners, photovoltaic panels, cooling towers, among others, and data related to thermal grids.

While examining the data from SG, some observations were made in regards to the type of information that would be inserted into the Brazilian database:

- Some official sources were already clear to be useful from the very beginning, such as several NBRs, created by ABNT (Brazilian Association for Technical Standards or *Associação Brasileira de Normas Técnicas*, in Portuguese); energy efficiency evaluation methods such as INI-C (in Portuguese, *Instrução Normativa INMETRO para a Classificação de Eficiência Energética de Edificações Comerciais, de Serviços e Públicas*) and INI-R (version for residential buildings) created by INMETRO (National Institute of Metrology, Quality and Technology or *Instituto Nacional de Metrologia, Qualidade e Tecnologia*, in Portuguese), energy data from EPE and ELETROBRAS, among others. ASHRAE standards were also considered in case no local regulation was found due to the fact that several NBRs do reference them as a complement in some cases;
- In regards to the variables and terms that were not applicable to Brazil or that needed some type of adaptation to a local reality:
    - When it comes to electricity and energy distribution, the definition of “district” is not widely used in Brazil as it is in CEA. Nationally, in terms of electricity supply, as previous data have shown, the majority of the buildings is connected to the local electrical energy utility companies (in Minas Gerais, for instance, it falls under the responsibility of CEMIG) -

which involves the building scale - while a still small portion of users produce electricity for their buildings through on-site generation with, in most cases, photovoltaic panels. When it comes to energy supply, more specifically thermal energy, two situations are present in Brazil as the energy chapter described: for water heating, electricity from the power utility companies is turned into thermal energy in showers or it is obtained through solar collectors; and for cooking purposes, LPG and natural gas can be used. The first two are based on a building scale, with showers and gas canisters being individual and punctual solutions, and the third one generally is linked to a gas distribution company (in Minas Gerais, GASMIG) that usually provides distribution networks through some parts of the city to be connected to buildings. Therefore, the areas to be simulated were defined by the number of buildings and the BR database would only have supply options linked to building or city scales;

- Heating systems would not be included due to the local climate of the studied areas not requiring such strategy, keeping only the cooling options. In the event of the current BR database being expanded to cover a larger variety of territories in Brazil, such as the Southeast region where the cold seasons are far more severe, then adding this strategy would become useful;
- Variables dealing with hot water for HVAC systems were also excluded because the main types of cooling systems included do not need this element to function. However, the logic from the previous bullet point is also true in this case;
- The “Thermal grid” file, present in the SG database, would need adaptation due to the fact that such a strategy is currently not common in Brazil. And since the software would need a database with said file, all the values included in this one in BR were illustrative and a note explaining such a decision was included in the cells of the table. It was noted that, if this table was destined to thermal energy used for cooking, it would get closer to a Brazilian scenario;
- Some uses in the USE_TYPES folder would be kept in the BR database and others would get excluded. The two main reasons for that

are linked to the available data in the regulations where such information was extracted from (energy efficiency methods called INI-C and INI-R), which had a relatively limited list of uses, and the available time frame for the present research. A combination of the two impacted on how diverse BR would be in terms of building uses. Additionally, some uses were adapted for similar reasons: educational institutions would be represented by PR_SCHOOL (primary school), healthcare facilities would be represented by HEALTH_UBS (UBS standing for *Unidade Básica de Saúde*, or Basic Health Unit) and foodstores would be represented by MARKET;

- Speaking of uses, it was noticed during the analysis of the SG database and the initial data compilation for the BR one a slight difference between the two contexts when it comes to a variable called "window-to-wall ratio", a measure to express the proportion between opaque external walls and their glazed areas: while in the SG database, such values were defined for each construction standard, that varied mostly from residential to commercial, in the Brazilian documentations used said measure is defined by use typology (retail, restaurant, offices, etc.). That would impact the BR database in a way that it would need to offer more standard options than the original folder to try to cover a larger number of use types and comply with the software logic: while SG offered 05 construction standard options, BR contained 15 standards, as it is discussed in the next section;
- Some energy options on "Feedstocks" and "Conversion" were reduced due to the available time frame to detail all of them and, most of all, the need to prioritize what was more relevant in the two studied areas. An eventual database expansion could alter this point and bring more options that are relevant in other Brazilian cities or states, if necessary;
- Still regarding "Feedstocks", other three adaptations were already envisioned during the investigation of the original database. First, the idea of "grid" in Brazil would work differently: in the BR database, GRID would be representing SIN (National Interconnected System, or *Sistema Interligado Nacional*, in Portuguese), the Brazilian electricity production and distribution system that is composed by multiple energy

sources, such as hydropower plants and solar. The name “grid” was kept only because, when tried to be changed to “SIN”, the software would eventually signal an error message. Second, only the main electricity sources would be kept from the original SG database to the first version of the BR one - them being the grid/SIN and solar - due to the fact that the units used by the original database considered only kWh, an electrical energy unit. This detail also brings to the discussion the third envisioned adaptation seen while examining the SG database: since the unit adopted in this table by SG involves kWh, any thermal energy sources that were destined to cooking (mostly natural gas and LPG) would be excluded from the future Brazilian database due to units incompatibility and the inability of CEA to currently analyze this type of data. This scenario, which illustrates a socioeconomic vulnerability in Brazil, would eventually be characterized as one of the main drawbacks in terms of the suitability of CEA in a Brazilian context, along with emissions and appliances, both to be mentioned in this section;

- Another significant drawback detected is linked to emissions. For starters, data regarding embodied CO_2 emissions from construction materials and systems is extremely difficult to find in Brazil, if not non-existent. With local documents being incipient in this regard, the focus was to search this information in international documentation such as EPDs (Environmental Product Declarations). However, another case of unit incompatibility was found: while the original database worked with data in $kgCO_2/m^2$ (kilos of carbon dioxide per square meter) - in the tables, “KgCO2m2” -, the unit found in EPDs was $KgCO_2eq$ (kilos of carbon dioxide equivalent), making it unlikely to be able to be converted properly. For these reasons combined, the sections dealing with emissions from materials in the BR database are defined with an illustrative value (set as “1”), so that the software would not read it as an error, accompanied by an explanatory note. That would, consequently, make the emissions analysis with the current version of the BR database pointless. Although this is one of the main drawbacks in the BR database when it comes to embodied carbon, an additional piece of information reduces the burden of this information

> gap: the Brazilian building stock is not a prominent problem when it comes to operational carbon emissions in the country. The 2024 National Energy Report pointed out that the transportation sector was the most representative, responsible for 217 MtCO2-eq of emissions. The residential sector, for instance, reached 18,4 MtCO2-eq in 2023 (EPE, 2024).

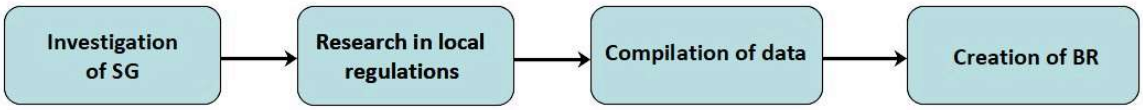
Additionally to variables that were either excluded or adapted, it was also noted that the absence of some crucial local information would also impact the vastness of the BR database. However, the problem in this case was not a lack of local information, but the current inability of CEA to consider such data. For instance, when it comes to hot water consumption and cooling solutions, two examples of appliances that are present in Brazil are electric showers and fans, respectively. As explained in the beginning of the present research, the former is an example of a punctual and easier solution that a considerable part of Brazilians possess at home, but in the "appliances" part of the schedules tables it was not possible to specify it separately. The latter, on the other hand, is a much more popular and affordable cooling solution in Brazil when compared to complex air-conditioning systems, such as split, window or even central systems - the ones the original database and CEA cover. It is believed that the impossibility to include this type of information would distance the analysis created by CEA with the BR database from crucial situations present in a Brazilian socioeconomic context.

Besides analyzing the SG database itself, the official CEA documentation, released on March 9th, 2023 and available on the software website, was also examined to, among other things, find the meaning behind the abbreviations and symbols used by CEA. Although the material helped in the majority of the process, even if it was about a previous software version (3.32.0), there were some variables with explanations that were insufficient to a complete understanding. This is further addressed in subsection 4.2.3.3.

4.2.2 Compilation and organization of local data

After understanding the SG database in detail, the research of local regulations started and all the useful data was put together in another table (partially illustrated by Image 45), where information that would eventually feed the BR database was organized. This table was, by far, the most robust one and contained mainly data from national regulations, norms, reports, papers, among others. All the used sources are compiled at the end of the present document, where every reference used in BR is stated. This process is briefly summarized in Image 50.

Image 50: Summary of the steps with the CEA databases



Source: Created by the author.

Among the main Brazilian sources, it is possible to mention several NBRs, created by ABNT, evaluation methods such as INI-R and INI-C, reports made by EPE and ELETROBRAS, etc. The vulnerabilities were identified in this table by using colors, signaling which variables would be problematic due to units incompatibility (example: emissions) or lack of data in local documents (example: construction tightness values), information that was unavailable in local regulations and that would need to be substituted by data from the original database (example: the “parameter in the investment cost function” variables mentioned in the previous section) and information that would have an explanatory note (example: interest rates in PV panels, which were defined based on information gathered from a paper).

Gathering enough information from local documents to fill some specific variables in the Brazilian database was another obstacle found during this process. Three scenarios were faced during this process, as illustrated by Image 51. It is worth mentioning the “educated guess” approach is a strategy used in the original database itself and it refers to a guess based on experience and scientific knowledge.

Image 51: Scenarios faced when prioritizing the data to feed BR

Source: Created by the author.

Both databases deal with a massive amount of information. However, as a brief list with examples of variables, it is possible to mention construction characteristics (building standards linked to building uses; construction systems such as walls and roofs; tightness values; window-to-wall ratio of façades in every cardinal direction; variables linked to the buildings gross floor area, such as the proportion of air-conditioned area; number of floors above and below ground, as well as the buildings height; among others); information linked to HVAC systems (types of cooling systems, controller and ventilation data; setback and setpoint temperature for cooling systems, etc.); data linked to indoor comfort and internal loads such as relative humidity, for instance; electricity supply; several equipment such as PVs, PVTs, solar collectors, boilers, among others.

The options that were used to define some variables in the BR database, such as construction systems, predominant HVAC systems and main energy sources, were taken from the data informed by Table 02, in the energy chapter. From this point onwards, the needed information was gathered from the other sources previously mentioned. In order to avoid mentioning any manufacturer name, additional sources such as papers were prioritized. In those documents where manufacturers were mentioned, such as the equipment and appliances efficiency tables by INMETRO, the strategy used to gather information was to use the mode values (the most frequent results) to keep the process as unbiased as possible.

One example of information that had to be adapted in BR, although not a negative one this time, is the conversion of monetary values from Brazilian Real (BRL) to United States Dollar (USD) in order to follow the same logic as the original database and CEA itself. Most values from Brazilian documents were, in fact, already stated in dollar. However, those which were not were converted before being added to the database and the exchange rate used was mentioned in every table where it appeared, as well as the date and data source. It would be interesting from a local standpoint to have all the values in the database in the local currency, but as mentioned before, it does not classify as a drawback nor does it diminish the pertinence of the database in regards to data of this nature.

Once every variable was collected from local documents, the manual process of filling each file of the BR database started, as the next section points out. It also highlights some vulnerabilities identified in the local database, in national regulations and in the CEA and SG database as well.

4.2.3 Database creation and test simulations

Following the same logic as the original database but with local data, the BR one was then created. Its contents take into account all the information stated previously, including what is mentioned in Tables 08 (basic content), 14 (excluded and adapted variables) and 15 (examples of information added into the BR database). It is important to mention that, as stated in the methodology chapter, two versions of BR were created in this research: the main one, directed for the CEA version used during this work (3.34.2) and an adaptation of it destined to the latest software update (3.37.x). The information was identical in both, with punctual changes in the latter to enable the new CEA to read it properly, following the new logic of its databases as well. Another point to emphasize is that both versions of the BR database were mainly destined to Belo Horizonte, Matozinhos and any city that presents similar urban and energy scenarios. The alterations made in BR 3.37.x when compared to the original BR 3.34.2 are summarized in Table 16.

Table 16: Modifications made in BR 3.37.x when compared to BR 3.34.2

FOLDER	ALTERATIONS IN BR 3.37.X
ARCHETYPES	No alterations made between databases
ASSEMBLIES	- “SUPPLY_NEW” table no longer exists. In the SG database it was merged with “SUPPLY” and, in BR, it was just a copy of the original file; - New files: ENVELOPE, SUPPLY and HVAC.
COMPONENTS	- “CONVERSION_NEW” table no longer exists for the same reason mentioned; - New files: CONVERSION, DISTRIBUTION and FEEDSTOCKS; - ENERGY_CARRIERS table was merged with the FEEDSTOCKS one, being now a tab in it; - In said tab, the variables "unit_cost_USD.kWh" and "unit_ghg_kgCO2.kWh" were also merged and became "COST_AND_GHG_TAB", which references the energy options available in the Feedstocks tab of this table; - CONVERSION: An additional variable is added, called “G_VALUE”. Besides, the names of every equipment is now written in capital letters.

Source: Created by the author.

Additionally to its default files, a .txt note was added in the main folder of BR 3.34.2 to provide a brief disclaimer to its users. Since the default options set in the “CONSTRUCTION_STANDARD” table were defined to describe common urban realities of Belo Horizonte and Matozinhos, this .txt file contains the following message meant to briefly guide the user in terms of considerably important data to be carefully checked depending on the scenarios to be simulated:

> The following tabs are crucial to be checked in each area to be simulated, since they can vary drastically depending on the urban context:
> - Envelope_assemblies
> - HVAC_assemblies
> - Supply_assemblies
>
> Note: Due to the complexity of the Brazilian urban and energy scenarios, this first version of the BR database is not applicable to the whole country and may need expansion to cover more data variability (DE MORAIS, 2024).

This note also emphasizes that the current version of BR is not necessarily applicable to the whole country, depending on the urban and energy scenario studied and that eventual expansions of its data may happen in order to offer more variability and, consequently, cover more Brazilian territories and realities.

Speaking of construction standards and recapitulating what was mentioned in section 4.2.1, the BR database offers triple the options of standards when compared to SG: 15 variations (Image 52). The reason for this is to enable said database to be as vast

as possible in terms of building typologies, while also following the original database logic when it comes to linking window-to-wall ratio values to construction standards.

Image 52: Construction standards in BR

STANDARD	Description
STANDARD1	Concrete and masonry - RESIDENTIAL (intermediate Window-to-Wall Ratio values according to NBR 15575-4/2021)
STANDARD2	Drywall - RESIDENTIAL (intermediate values for WWR according to NBR 15575-4/2021)
STANDARD3	Concrete and masonry - RESIDENTIAL (higher WWR according to INMETRO decree number 309/2022)
STANDARD4	Drywall - RESIDENTIAL (higher WWR according to INMETRO decree number 309/2022)
STANDARD5	Concrete and masonry - RETAIL, main façade facing EAST (according to INMETRO decree number 309/2022)
STANDARD6	Drywall - RETAIL, main façade facing WEST (according to INMETRO decree number 309/2022)
STANDARD7	Concrete and masonry - OFFICE (WWR according to INMETRO decree number 309/2022)
STANDARD8	Drywall - OFFICE (WWR according to INMETRO decree number 309/2022)
STANDARD9	Concrete and masonry - OFFICE (higher WWR)
STANDARD10	Drywall - OFFICE (higher WWR)
STANDARD11	Concrete and masonry - HEALTHCARE FACILITIES (UBS in Portuguese) - WWR according to INMETRO decree 309/2022
STANDARD12	Drywall - HEALTHCARE FACILITIES (UBS in Portuguese) - WWR according to INMETRO decree 309/2022
STANDARD13	Concrete and masonry - PRIMARY SCHOOL (WWR according to INMETRO decree 309/2022)
STANDARD14	Drywall - PRIMARY SCHOOL (WWR according to INMETRO decree 309/2022)
STANDARD15	Concrete and masonry - ATYPICAL SETTLEMENTS

Source: Created by the author.

The standards follow a pattern in terms of data variation. There are mainly 05 uses being represented: residential buildings, retail, office, healthcare facilities and schools. They varied either in construction techniques - masonry, the most prominent in the country, and drywall - or in window-to-wall ratio values, according to data taken from INMETRO decrees and NBRs. Additionally, a specific standard dedicated to atypical settlements is also part of the BR database. Its purposes were to illustrate these types of buildings that are considerably representative in Brazilian cities and reflect a relevant socioeconomic reality, as well as investigate CEA sensibility to them during simulations.

Once the BR database was formally set, test simulations were run to check if the files were working properly and if eventual errors would appear to be, then, solved. Among the error messages spotted, two are given as examples:

- A message pointing to certain table cells that did not accept “NA” (not applicable) as valid values, such as the setpoint and setbacks temperatures for heating, a variable that would not be used in this version of the BR database. As an attempt to solve this problem, the same cells were filled with “0” (zero), value that would not be reached in the studied microclimates under normal conditions;

- A message would appear after changing the name “GRID” to “SIN” in the Feedstocks table, in order to identify said energy source as the Brazilian interconnected system. As an attempt to solve this error, the name was changed back to “GRID” and an explanatory note was added.

Once every error was eliminated and the BR database was fully functional, the formal simulations of this research were run and results gathered. However, before reaching this section, it is worth listing some observations drawn regarding vulnerabilities that were detected in the BR database, in local documents and in the software itself, as well as its own original database, throughout this entire process. It is significantly important to emphasize that this section is not pointing defects out, but rather clarifying some obstacles faced during the research development and the process of reconciling documents and software simultaneously, while also taking the nuances of a Brazilian scenario into account.

4.2.3.1 BR database: Detected vulnerabilities

As examples of obstacles faced during the research in terms of building the BR database, it is possible to mention:

- The variables that were excluded, especially the emission-related data due to units incompatibility between the software and the information sources available;
- The variables that had their values taken from the original database due to a lack of official local information regarding them, such as the data on the Controller tab, in the HVAC table, “moisture released by occupancy at peak conditions” (X_ghp) and “equipment interest rates” (IR_%). There is also information taken from SG and put into BR that might be impacted by the location, such as the “parameter for air mass modifier” (Pv_a0). According to KLISE et a. (2015), however, this topic showed the need for expansion in scientific literature:

> "To our knowledge there are few, if any, investigations into the potential variability of a module’s air mass function across locations with varying climate. (...) The variation in air mass functions at different locations has not previously been explored because suitable data and appropriate analysis techniques have not been available."

- Data regarding “internal heat capacity per unit of air conditioned area” (Cm_Af), although not taken from the original database, was collected from a draft standard that is currently in discussion in Brazil: the adaptation of ISO 52016/2017, which could change when it eventually becomes official. However, it is relevant to point out that the values show a distinct connection to what it is defined in the original standard, but with an adaptation to reflect the local reality;
- The technical definitions in the HVAC table, such as “convective part of the power of the cooling system in relation to the total power” (convection_cs), “set-point correction for space emission systems” (dTcs_C), “supply air temperature of the air-handling units” (T_sup_air_ahu_C), among others. Since this type of data was not found in local regulations and air-conditioning systems is not the area of expertise of the author, it is hypothesized that the mentioned data can only be found either in a manufacturer’s technical manual or defined by an air-conditioning project;
- The information within a table called “Distribution”, for the same reasons as mentioned in the previous topic;
- The amount of building uses present in the “Use_Types” folder was limited due to the lack of information regarding other uses in local legislations. This list could be expanded as a future research;
- A specific use schedule for churches would be a useful complement to the BR database, since they were relatively common in the studied areas and this scenario also applies to other Brazilian territories. In the simulations presented in Section 4.3, they were defined with the schedule of schools due to a lack of such data in local regulations to enable the creation of said file;
- Data availability: it was noted that tracking more detailed data about buildings, especially from a small town such as Matozinhos, proved to be a challenge. Local information regarding most common HVAC systems in buildings was non-existent. This is a scenario that will probably repeat itself in other Brazilian territories, especially in small cities.

4.2.3.2 Local regulations: Detected vulnerabilities

As some examples of obstacles faced during the research in terms of the data found in the local official documentation examined, that is available online, it is possible to mention:

- Data regarding construction tightness values were not found;
- More detailed definitions for each area of the country, as it is done in some international standards such as ASHRAE-55. In a Brazilian scenario, the areas would probably be the bioclimatic zones in which the country is divided, for instance;
- Shading coefficient of elements that are commonly found in some building typologies, such as awnings (*toldos*). It is also worth mentioning that the other elements present in the BR database had their coefficient taken from international regulations such as ISO 52016-1/2017.

4.2.3.3 CEA and original database: Detected vulnerabilities

Finally, as examples of obstacles faced during the research when it comes to CEA and its database structure, it is possible to list the following:

- As mentioned before, there were some appliances that are considerably present in Brazilian scenarios when it comes to hot water consumption and cooling, such as electric showers and fans, respectively. They are usually more affordable and simple solutions that can be installed in any building. There are local data to be fed into a database, but since the software does not analyze such punctual solutions and opt for more robust HVAC equipment, it is not possible to insert these types of appliances into BR;
- A similar thing happens when LPG, wood and natural gas are involved in the energy matrix. In Brazil, LPG and wood are mostly used for cooking purposes - therefore, thermal energy - and the context given in the energy chapter actually illustrates a social vulnerability at a time when part of the Brazilian population struggled to purchase LPG and had to resort to precarious palliative solutions while prices were fluctuating. And although still representing a small percentage, natural gas has been increasing in the Brazilian matrix and it is used as a thermal energy source as well for purposes such as water heating and cooking. Since the Feedstocks table and the

"Energy_Carriers" tab work with an electrical energy unit (kWh) when dealing with selling and buying costs and such correspondence was not found when referring to the mentioned sources, they were not able to be added to this first version of the BR database;

- Another crucial topic of analysis in a considerable portion of Brazil is natural ventilation. Cross ventilation, for example, is a fundamental passive strategy in many areas of the country and, if buildings are planned accordingly to use the most out of it, this factor can actually impact positively on the energy demand since it reduces the need for artificial cooling. During this research, it was not noticed any relevant way in which such scenario could be included in the database or in the simulations, for that matter;
- When dealing with window-to-wall ratio values, CEA only considers cardinal points (north, south, east and west). An environment that can be developed in a fluid way such as the urban fabric, especially in cities that grow without planning, presents buildings with façades pointing to more than just these four main directions. It would be interesting if there was a possibility of adapting this in a way that it could eventually include buildings with façades pointing towards northeast, northwest, southeast and southwest, for example;
- The variable "void_deck" ("number of floors, from the ground up, with an open envelope") has a relatively vague definition. Questions as to whether this refers to an opening for natural lighting or ventilation and if any size would count were raised. In Brazil, the closest definition to it in local regulations would be the opening percentage (*percentual de abertura*, in Portuguese). However, it is still not possible to define one single value to each construction standard because other variables from the same local legislation can impact on such a number. For instance, this value can vary depending on whether the ambient is one for prolonged or transitory stay. That means that such variable would need to be defined by the user for each building;
- There was an attempt to add an option in the SUPPLY_ELECTRICITY tab that could link the electricity matrix to solar generation through photovoltaic panels. However, the software did not allow the use of SOLAR as a feedstock, only GRID. It is relevant to mention that in the original database studied there is only the use of GRID as well;

- In terms of the official documentation, it is undeniable that it offered considerable help in identifying the meaning and purpose of several variables in the original database. However, some terms were slightly vague and did not offer further clarification. For instance, the variables “a”, “b”, “c”, “d” and “e”, linked to a specific equation present in several equipments such as vapor absorption chillers and photovoltaic panels, were all defined in said equation as “parameter in the investment cost function”. This made it difficult to find related local information and would eventually culminate in the adoption of data from the original database (SG) as part of the BR one. More detailed definitions can be helpful during the information research to feed or update databases, for example.

With these steps thoroughly covered and context fully provided, the next phase to address pertains to the simulations of the three studied areas, using both SG and BR databases: Lourdes (BH1), Céu Azul (BH2) and downtown Matozinhos (MTZ1).

4.3 Phase 3: Research simulations

The simulations run in the three areas mentioned followed the same logic, varying only the urban characterization. After the input data was set in each area and the simulations were performed, the results were collected for further analysis. As the title of this research highlights, said analysis mainly focused on investigating the potential and suitability of CEA in Brazilian contexts.

To each urban area, a collection of buildings were chosen to be studied in more detail and the reason for that lies in the massive amount of buildings being simulated (307 in total), making it unlikely to analyze all of them properly in the present work. In order to focus the analysis and better compare results, one sample of each relevant use was chosen. They are pointed out in the sections of all the three regions.

The three studied areas are addressed separately in the following sections under a similar structure:

1. First, the input definitions are illustrated, with a picture of said urban region; the weather file used in that scenario; the information chosen for the “Input Editor” tables (Zone, Typology, Architecture, Internal Loads, Indoor Comfort, Air-conditioning Systems, Supply Systems, Surrounding and Schedules) and

the information set for the “Tools” tabs (Data Management, Demand Forecasting and Energy Potentials);

2. The variables chosen as output to be analyzed, already mentioned in the methodology section;
3. Results comparison between the SG and BR databases, analyzing the buildings chosen as samples in each scenario.

4.3.1 Lourdes - Belo Horizonte (BH1)

The section of the *Lourdes* neighborhood chosen to be simulated can be briefly summarized by an economically thriving region with multiple building uses in its territory, ranging from single-family residences to apartments, restaurants, office towers, retail spaces, healthcare facilities, among others. The building heights tend to vary as well, with multiple examples of high-rise constructions.

4.3.1.1 Input definitions

BH1 contains 112 buildings spread among 06 blocks, as Image 53 illustrates. For this area, the weather file “Belo Horizonte-Carlos Prates”, with a compilation of data between 2007 and 2021, was chosen. And, as with all of the three analyzed areas, the CEA databases included in said simulations were the original SG and the recently created BR.

Image 53: BH1

Source: CEA. Modified by the author.

The input data was divided into two sections: the information contained in the “Input Editor” option in the software (09 tables in total, including the 3D geometry) and the variables present in the “Tools” button, where the simulation scripts are located. For all the three areas, the tables on “Input Editor” were set with the available option of each CEA database, according to what was more suitable for each scenario. As for the 3D geometry, it was taken directly from OpenStreetMap.

Through a more detailed lens, the settings defined for BH1 with both SG and BR databases in the Input Editor tables are described in Table 17.

Table 17: Input settings for BH1, with SG and BR databases (“Input Editor” tables).

	BH1_SG	BH1_BR
Zone	Taken from OpenStreetMap, with no floors below ground being adopted. **Alterations - "floors_ag":** B1000 (2 floors); B1002 (2); B1003 (2); B1004 (2); B1005 (2); B1007 (14); B1021 (2) and B1067 (10). **Height of each floor = 3 meters each**	Same settings as BH1_SG. **Extra alterations - "floors_ag":** B1030 (2 floors); B1076 (16); B1070 (10); B1029 (2) and B1026 (19). **Height of each floor = 3 meters each**
Typology	**Use adaptation:** B1020 (from MULTI_RES to HOSPITAL, since it is a health clinic); B1067 (0.9 OFFICE and 0.1 RETAIL). Some standards were changed to match the defined uses. **Standards:** MULTI_RES and SINGLE_RES set as STANDARD1 (Exceptions set as STANDARD2 (higher air conditioned area due to higher WWR: B1007, B1083, B1081, B1076, B1036 and B1047); HOSPITAL , RETAIL, OFFICE and RESTAURANT set as STANDARD3.	Mostly from the BR database. **Use adaptation:** B1020 (from MULTI_RES to HEALTH_UBS); B1002 (from HOSPITAL to HEALTH_UBS) and B1067 (0.9 OFFICE and 0.1 RETAIL). Some standards were changed to match the defined uses: MULTI_RES and SINGLE_RES set as STANDARD1 (Exceptions: B1007, B1083, B1081, B1076, B1036 and B1047 - STANDARD3); HEALTH_UBS set as STANDARD11, RETAIL set as STANDARD5, OFFICE set as STANDARD7 (exception: B1067 - STANDARD9) and RESTAURANT set as STANDARD5.
Architecture	Defined by the SG database after the standard alterations on "Typology". **Exceptions:** TIGHTNESS = AS5; ROOF = AS2 (all); AS3 (B1020; B1006; B1003; B1002) and AS1 (B1076).	Defined by the BR database after the alterations on "Typology". **SETTINGS - All buildings:** CONSTRUCTION_AS2; TIGHTNESS_AS5 (exceptions: B1067- AS3); ROOF_AS1 - concrete slab (exceptions: B1000, B1004, B1021, B1067 - AS2; B1002, B1003 and B1005 - AS4); SHADING - Defined by each use/standard (exception: B1000 and B1003 - AS6; B1021 - AS7); WALL_AS2 (exceptions: B1001 - AS3); WALL_AS2 (partition); FLOOR_AS1; FLOOR_AS1 (base); WINDOW_AS2 (exception: B1000 and B1021 - AS1;

		B1067 and B1082 - AS6; B1046 - AS3).
Internal Loads	Defined by the SG database	Defined by the BR database
Indoor Comfort	Defined by the SG database	Defined by the BR database
Air-conditioning systems	Defined by the SG database (Exceptions: B1020 - HVAC_COOLING_AS2; all - HVAC_HOTWATER_AS0). Due to the economic characteristics of this area, all buildings have some type of HVAC system.	Defined by the BR database. **SETTINGS - All buildings:** HVAC_COOLING_AS2 (exceptions: B1000 - AS0; B1026, B1029, B1030, B1070 and B1076 - AS1); HVAC_HEATING_AS0; HVAC_HOTWATER_AS0; HVAC_CONTROLLER_AS2 (exceptions: B1000 - AS0) and HVAC_VENTILATION_AS2 (exceptions: B1000 - AS0).
Supply systems	Defined by the SG database. **Exception:** SUPPLY_HOTWATER_AS0 (all buildings)	Defined by the BR database. **SETTINGS - All buildings:** SUPPLY_COOLING_AS2 [exceptions: B1000 - AS0; B1026, B1029, B1030, B1070 and B1076 - AS1]; SUPPLY_HOTWATER_AS0; SUPPLY_ELECTRICITY_AS1 and SUPPLY_HEATING_AS0.
Surroundings	Unchanged. Taken from OpenStreetMap	Unchanged. Taken from OpenStreetMap
Schedules	Defined by the SG database	Defined by the BR database.

Source: Created by the author.

In regards to the variables presented by the “Tools” button, where the simulation scripts are located, Image 54 summarizes the information inserted into each one of them for all studied areas. Once again, it is emphasized that all buildings were simulated in each area, but only a few were selected as samples to be discussed in detail.

Image 54: Input settings for the areas, with SG and BR databases (“Tools” button).

TABS	SCRIPTS	VARIABLES	SETUP
Data Management	*Archetypes mapper* **	*Not aplicable*	
	Weather helper	EPW files mentioned for each area	
	Surroundings helper	Buffer	100m (downtown) / 50m (others)
		Height	Definitions taken from OpenStreetMap
		Floors	
	Terrain helper	Grid size	30 m
		Elevation *(Data taken from the respective city councils websites)*	852 m (Belo Horizonte)
			772 m (Matozinhos)
	Streets helper	Bbox	*Left blank (default)*
		Streets	All
Demand Forecasting	*Building solar radiation*	Multiprocessing	TRUE
		Use latest Daysim binaries	TRUE
		Albedo	0,17 (Hot mix asphalt) (EUA, 20--)
		Debug specific behaviors	TRUE
		Number of buildings in chunk	100
		Write-sensor-data	TRUE
		Roof-grid	10
		Walls-grid *(Default: 200, 1 point)*	200 (1 point per surface)
		Zone-geometry	2
		Surrounding-geometry	5
		Consider floors	TRUE
		Consider intersections *(Intersections of walls between buildings)*	TRUE
		DAYSIM SIMUL. PARAMETERS	*Default*
	Building schedules	Multiprocessing	TRUE
		Schedule model	DETERMINISTIC
		Debug specific behaviors	TRUE
	Building energy demand	Multiprocessing	TRUE
		Buildings	*Select all*
		"Advanced" option - All set as "Default" definitions, **EXCEPT**:	
		Debug specific behaviors	TRUE
		Resolution output	HOURLY
		Overheating warning	FALSE
Energy potentials	*Photovoltaic-thermal panels*	Multiprocessing	TRUE
		Type-pvpanel	PV1
		Type-scpanel	FP
			ET
		Panel-on-roof	TRUE
		Panel-on-wall	FALSE
		Annual-radiation-threshold	800
		Max-roof-coverage	1
		Custom-tilt-angle	FALSE (Optimized value will be used)
		"ADVANCED" OPTION	*Default*
	Photovoltaic panels	Multiprocessing	TRUE
		Type-pvpanel	PV1
			PV2
		Panel-on-roof	TRUE
		Panel-on-wall	FALSE
		Annual-radiation-threshold	800
		Max-roof-coverage	1
		Custom-tilt-angle	FALSE (Optimized value will be used)
		"ADVANCED" OPTION	*Default*
	Solar collectors	Multiprocessing	TRUE
		Type-scpanel	FP
			ET
		Panel-on-roof	TRUE
		Panel-on-wall	FALSE
		Annual-radiation-threshold	800
		Max-roof-coverage	1
		Custom-tilt-angle	FALSE (Optimized value will be used)
		"ADVANCED" OPTION	*Default*

Source: Created by the author.

4.3.1.2 Output to be analyzed

As defined in chapter 3 (Methodology), in section 3.3 (Phase 3) and subsection 5 (Results to be collected).

4.3.1.3 Results comparison

In BH1, 08 buildings were chosen to be studied in more detail, as listed in Table 18.

Table 18: Sample buildings chosen for analysis in BH1.

CODE	BRIEF DESCRIPTION
B1000	Set as SINGLE_RES with HVAC systems using the SG database and without air-conditioning systems using BR.
B1002	Set as HOSPITAL with the SG database and HEALTH_UBS with BR.
B1003	Set as RETAIL with HVAC systems in both cases.
B1004	Set as OFFICE with HVAC systems in both cases.
B1005	Set as RESTAURANT in both cases.
B1007	Set as MULTI_RES with HVAC systems in both cases.
B1021	Set as SINGLE_RES with HVAC systems in both cases.
B1067	A multi-use building set mainly as OFFICE and secondly as RETAIL, with HVAC systems in both cases.

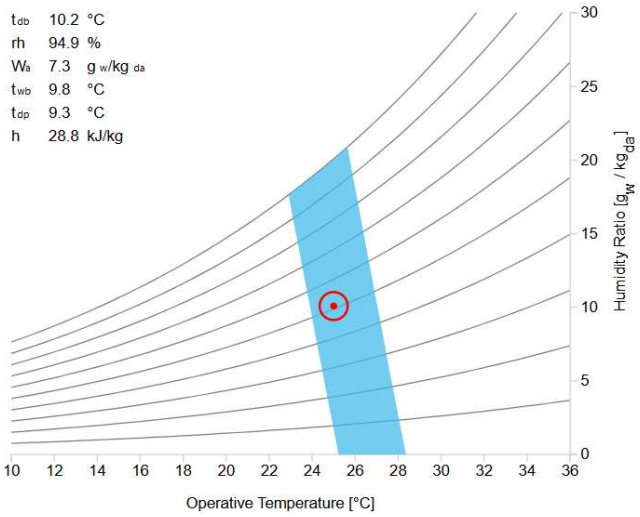
Source: Created by the author.

Comfort charts and energy balance graphs display a collection of data per building per image. The other graphs that show information of the whole area simulated do so in a broader way, with multiple buildings at the same time. Some results with both databases are compiled in A3 formats to visually enable a more straightforward comparison. This logic applies to all studied areas.

Comfort charts

Before discussing the results gathered in this section, it is important to first address the type of graph to be displayed and how information in it is shown. A psychrometric chart combines data regarding operative temperature and moisture to classify the amount of the 8760 annual hours spent in thermal comfort and discomfort in a specific city. The model used by CEA complies with the ASHRAE standard 55-2023, as illustrated by Image 55. The charts created by the software using both databases displayed only the hours during summer.

Image 55: ASHRAE psychrometric chart.

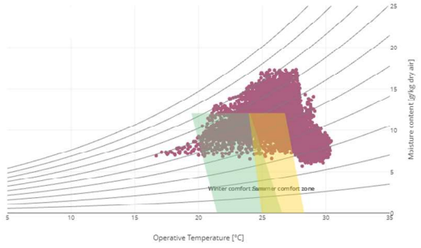


Source: TARTARINI et al., 2020.

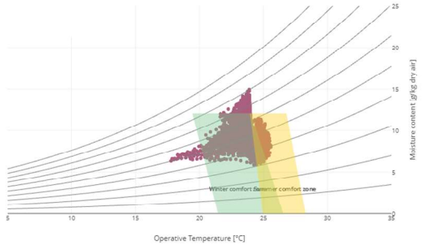
The following page compiles all the comfort charts generated for the sample buildings in BH1 using both the SG and BR databases, followed by the discussions regarding them.

Image 56: Comfort charts of buildings in BH1 (Lourdes/Belo Horizonte), with both databases.

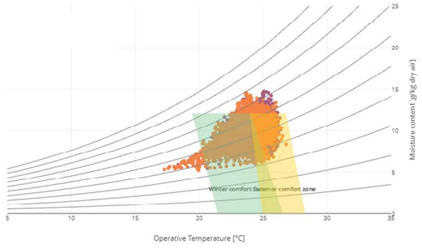
A - B1000 - BH1_SG



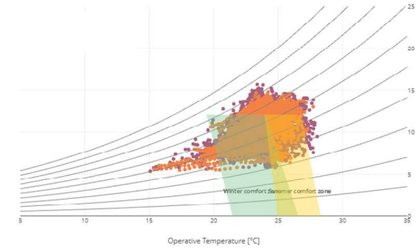
C - B1002 - BH1_SG



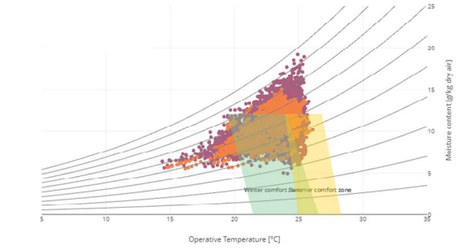
E - B1003 - BH1_SG



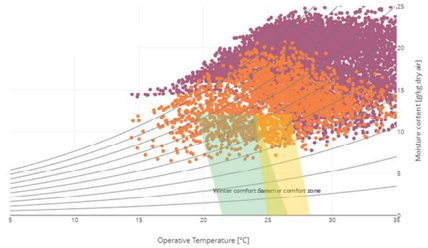
G - B1004 - BH1_SG



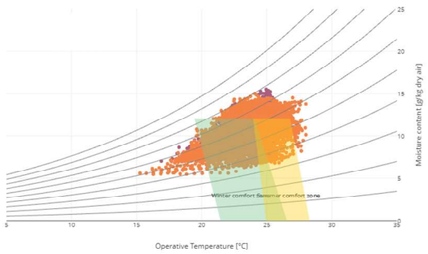
I - B1005 - BH1_SG



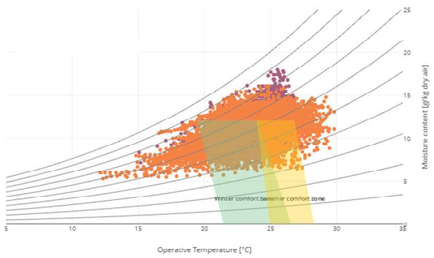
B - B1000 - BH1_BR



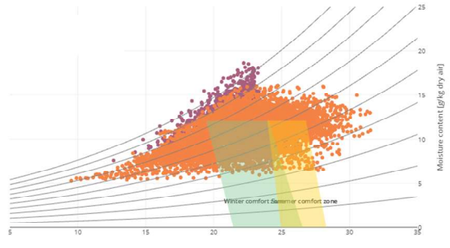
D - B1002 - BH1_BR



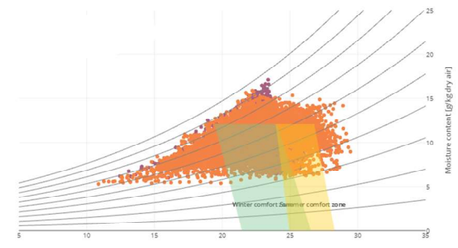
F - B1003 - BH1_BR



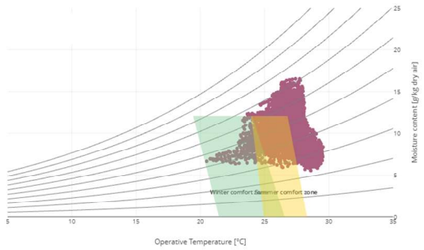
H - B1004 - BH1_BR



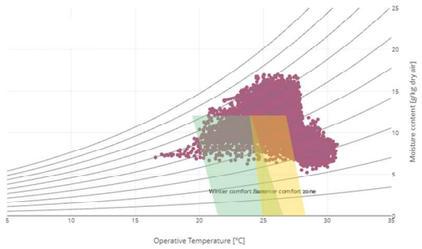
J - B1005 - BH1_BR



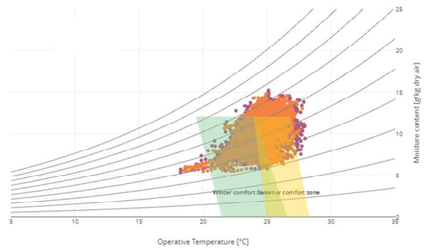
K - B1007 - BH1_SG



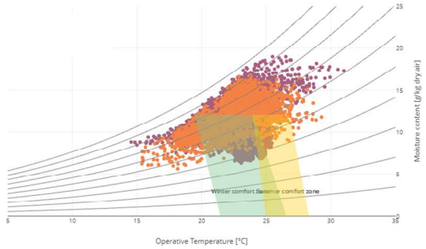
M - B1021 - BH1_SG



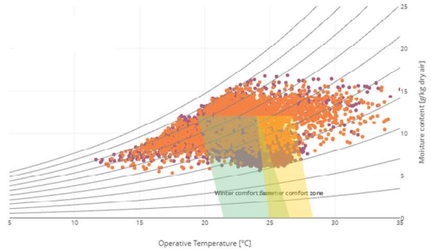
O - B1067 - BH1_SG



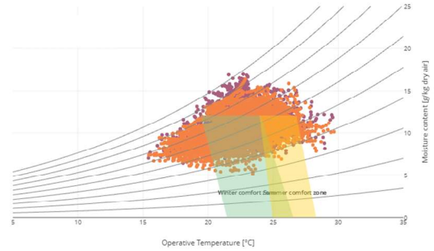
L - B1007 - BH1_BR



N- B1021 - BH1_BR



P - B1067 - BH1_BR



- Occupied hours summer
- Unoccupied hours summer

Source: CEA. Compiled by the author.

An immediate difference between the charts generated with SG and those from BR is the way the dots representing the annual hours are displayed: while in the former they are much more concentrated in the central areas of the chart, the latter presented them in a more scattered pattern. Another trait to be noted is that, in some charts from SG, only the occupied hours during summer were displayed, while in the others both occupied and unoccupied hours showed up. The fact that CEA only addresses hours during summer is a sensitive spot for Brazilian scenarios.

Some situations were not expected and raised questions. The pattern the annual hours followed in specific buildings, such as those represented by charts B, F and P (especially B), where part of them exited the chart area, were considered an anomaly. A doubt that was raised pertains to the reason why the winter comfort zone is displayed in the charts when no winter occupied or unoccupied hours are addressed.

Other platforms that generate psychrometric charts, such as Climate Consultant (responsible for Images 34 and 35), take only the chosen weather file into account to generate its results. Regarding CEA, since the weather file used was the same with both BR and SG databases, it is believed that the differences between them played a relevant part in the final results.

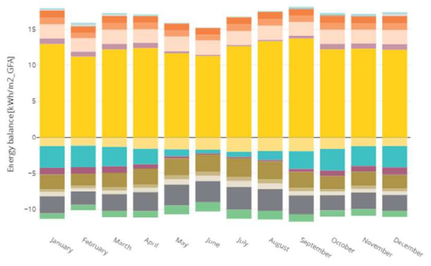
Energy Balance

During the analysis of the results, it was noted that the legend used by the CEA to display the charted data is not necessarily intuitive, since it is basically the abbreviation of multiple words separated by underscores ("_"), which creates an extra obstacle for the user during the analysis process. In order to clarify the variables in the charts before the analysis, each one of them are defined below. While some were found described on the software website, others were presumed according to each abbreviation and the type of unit they dealt with:

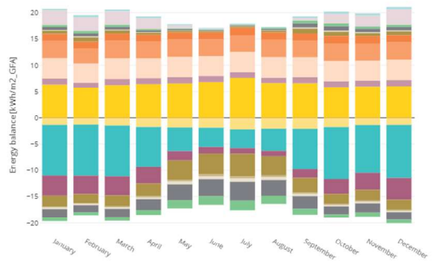
- I_sol = Solar heat gain
- Qhs_tot_sen = Total sensible heat involving heating systems
- Qhs_loss_sen = Sensible heat loss involving heating systems
- Q_gain_lat_peop = Latent heat gain from people
- Q_gain_sen_light = Sensible heat gain from lighting
- Q_gain_sen_app = Sensible heat gain from appliances
- Q_gain_sen_data = Sensible heat gain from data centers
- Q_gain_sen_peop = Sensible heat gain from people
- Q_gain_sen_wall = Sensible heat gain from transmission through walls
- Q_gain_sen_base = Sensible heat gain from transmission through the base
- Q_gain_sen_roof = Sensible heat gain from transmission through the roof
- Q_gain_sen_wind = Sensible heat gain from transmission through windows
- Q_gain_sen_vent = Sensible heat gain from ventilation and infiltration
- Q_gain_lat_vent = Latent heat gain from ventilation and infiltration
- I_rad = Radiative heat loss
- Qcs_tot_sen = Total sensible heat involving cooling systems
- Qcs_tot_lat = Total latent heat involving cooling systems
- Qcs_loss_sen = Sensible heat loss involving cooling systems
- Q_loss_sen_wall = Sensible heat loss through walls
- Q_loss_sen_base = Sensible heat loss through the base
- Q_loss_sen_roof = Sensible heat loss through the roofs
- Q_loss_sen_wind = Sensible heat loss through windows
- Q_loss_sen_vent = Sensible heat loss through ventilation and infiltration
- Q_loss_sen_ref = Sensible heat loss from refrigeration systems

Image 57: Energy balance of buildings in BH1 (Lourdes/Belo Horizonte), with both databases.

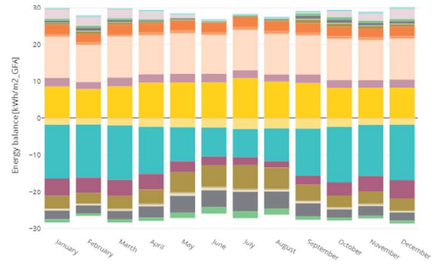
A - B1000 - BH1_SG



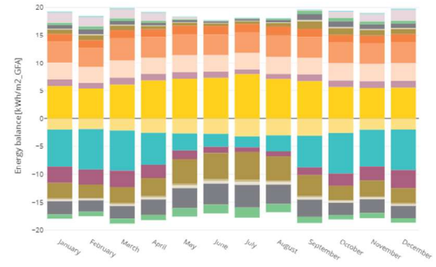
C - B1002 - BH1_SG



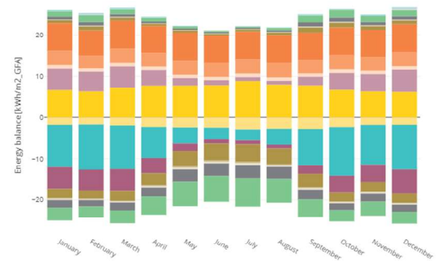
E - B1003 - BH1_SG



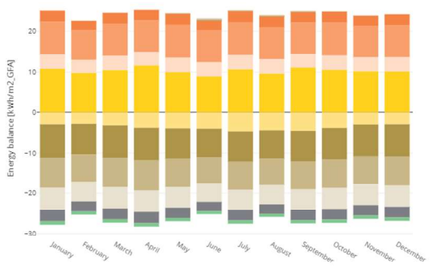
G - B1004 - BH1_SG



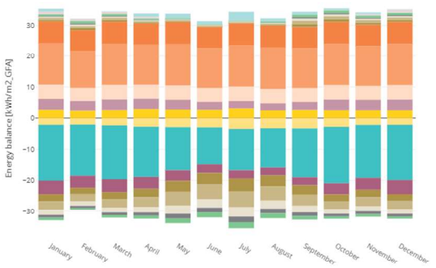
I - B1005 - BH1_SG



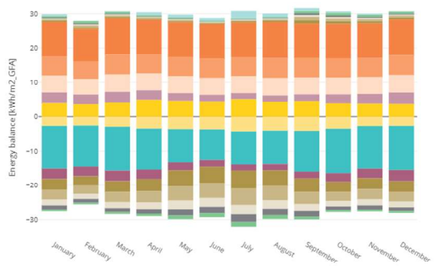
B - B1000 - BH1_BR



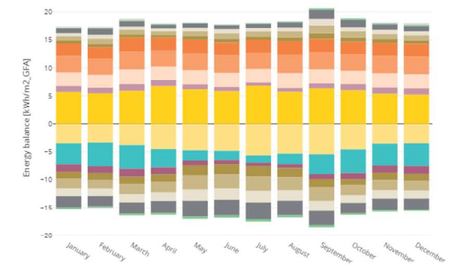
D - B1002 - BH1_BR



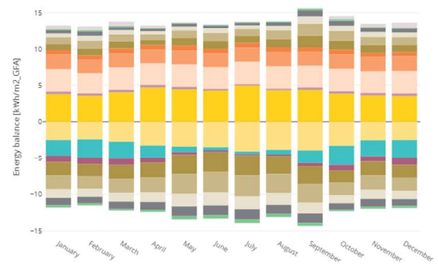
F - B1003 - BH1_BR



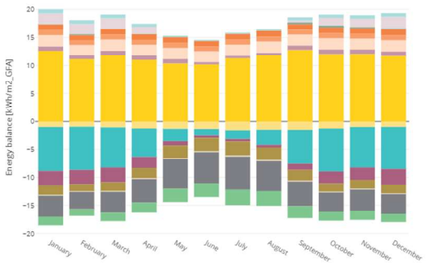
H - B1004 - BH1_BR



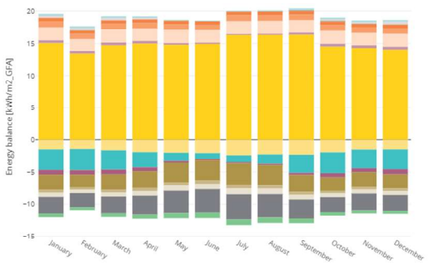
J - B1005 - BH1_BR



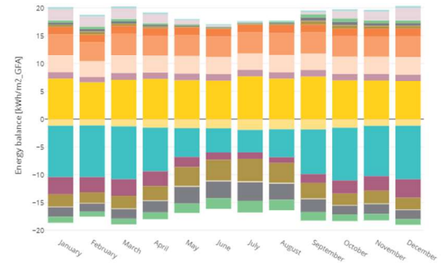
K - B1007 - BH1_SG



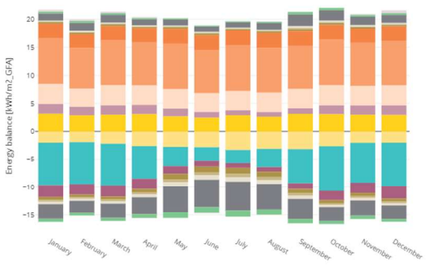
M - B1021 - BH1_SG



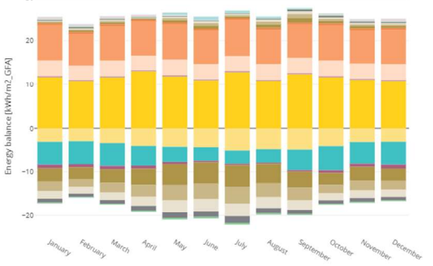
O - B1067 - BH1_SG



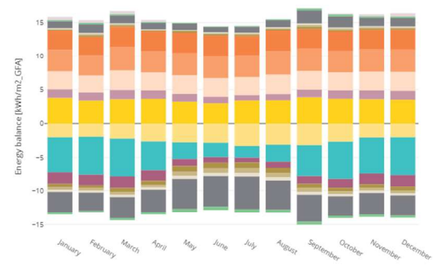
L - B1007 - BH1_BR



N - B1021 - BH1_BR



P - B1067 - BH1_BR



Source: CEA. Compiled by the author.

From a broader point of view, the majority of the graphs showed the same variables being mentioned whether it was generated from SG or BR. However, the values each variable reached, being gains or losses, fluctuated dramatically from database to database, which was expected due to the data differences between them. In terms of the most predominant variables linked to gains, it is possible to mention "solar heat gain" and "sensible heat gain from lighting" for SG and "solar heat gain" and "sensible heat gain from appliances" for BR. As for the losses, "total sensible heat involving cooling systems" was the most representative variable with the SG database and "total sensible heat involving cooling systems", "sensible heat loss through walls" and "sensible heat loss through windows" were the most prominent with the BR one. Data linked to lighting, people and appliances impacted in slightly different ways depending on the database used. Specific physical characteristics of building materials and other elements may have also impacted on the results from database to database.

It was noticed that, in most cases, the solar heat gain values reached the highest with the Singaporean database. In terms of WWR (window-to-wall ratio), BR and SG have similar values describing default options for residential buildings (around 0.29 in SG and 0.24-0.25 in BR) and default retail/commercial/office constructions (0.59 in SG and around 0.6-0.7 in BR). However, BR presents more variations in these values depending on the façade orientation and also has higher numbers when dealing with, for example, a variation of residential buildings - referencing those with more glazed vertical surfaces. Regardless, these differences were seemingly not enough to increase the solar heat gains while using BR.

The majority of values regarding “sensible heat loss through ventilation and infiltration” were higher with the SG database and lower with the BR one. This last result was not expected, since there are some definitions between the SG and BR databases that would rather reverse the situation: while they have similar settings for “void_deck” (number of floors with an open envelope), SG can present much lower WWR values in some of its construction standards when compared to the BR database. It was considered that this would also make the results dealing with losses from windows be abnormal, since not only there is a considerable difference between their WWR but also the fact that, in Brazil, window tightness requirements are not even nearly as high as in other countries with more rigorous climates.

Energy End-Use and Energy End-Use Intensity

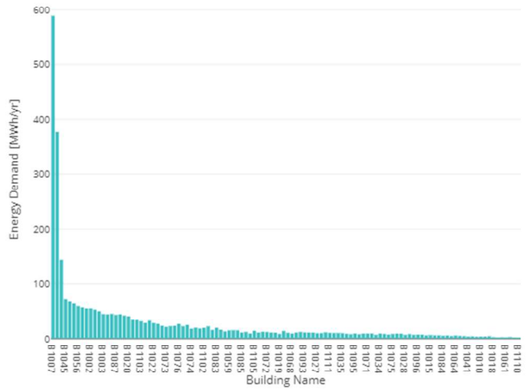
This section discusses the results from the graphs that display data regarding the energy directly consumed by the final user (Energy End-Use) and the intensity of such demands (Energy End-Use Intensity). In BH1, only B1000 did not have any HVAC system set before the simulations.

Due to the microclimate and specific needs of the studied areas, the air-conditioning systems were set so as to only present cooling demands throughout the year. Therefore, every heating-related variable was defined as "none" and, for this reason, both sets of graphs address only two topics: cooling and electricity demands, the latter also being linked to appliances and not only to HVAC systems. In order to better visualize the results on the graphs, cooling and electricity will be discussed separately. Another important note to make regarding CEA interface is that, due to the large number of buildings being simulated in each area, the graphs displayed in this work may not mention every single one of them in its X axis, meaning that its complete visualization would only be available in the software itself by zooming in each graph.

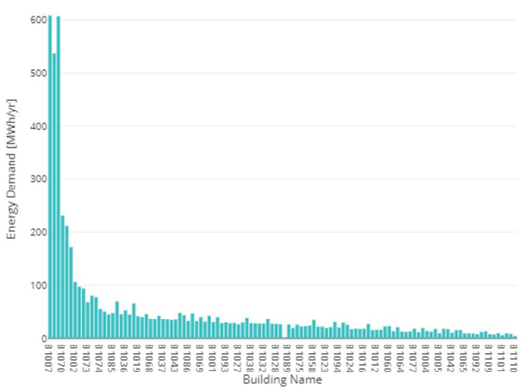
The graphs from BH1 addressing energy end-use and energy end-use intensity are compiled in the following A3 page.

Image 58: Energy end-use graphs of BH1 (Lourdes/Belo Horizonte), with both databases.

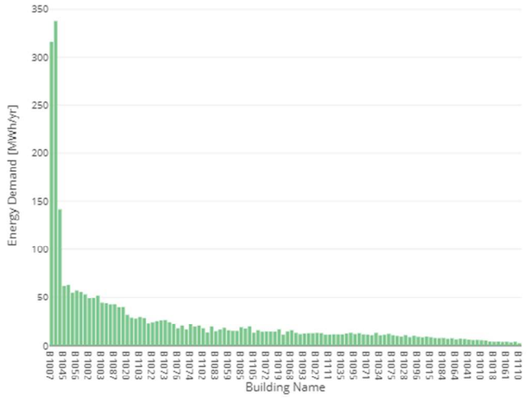
A - Space cooling demand only - SG database (BH1)



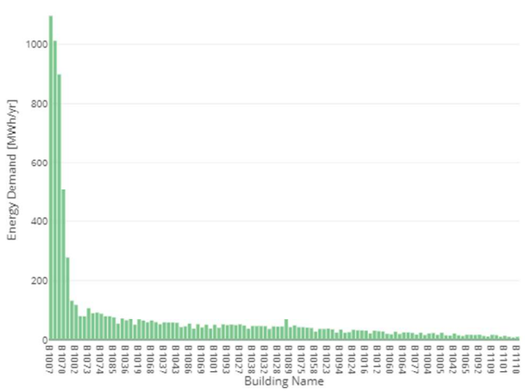
B - Space cooling demand only - BR database (BH1)



C - Electricity demand only - SG database (BH1)



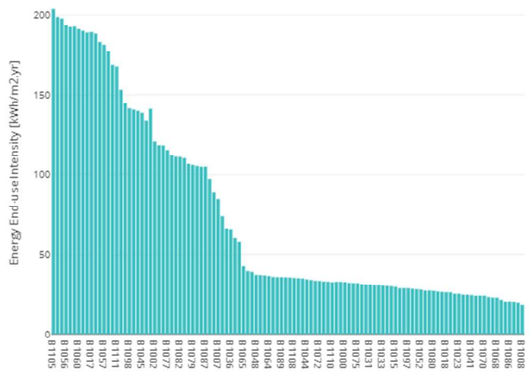
D - Electricity demand only - BR database (BH1)



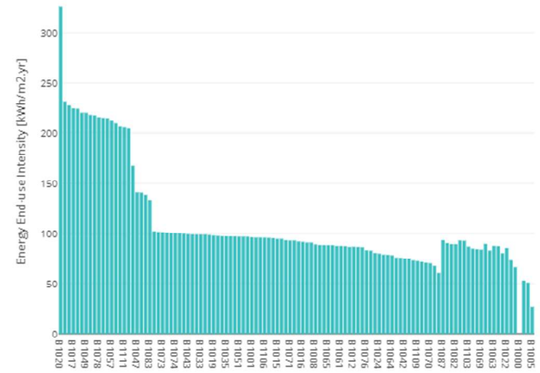
End-use space cooling demand
End-use electricity demand

Image 59: Energy end-use intensity graphs of BH1 (Lourdes/Belo Horizonte), with both databases.

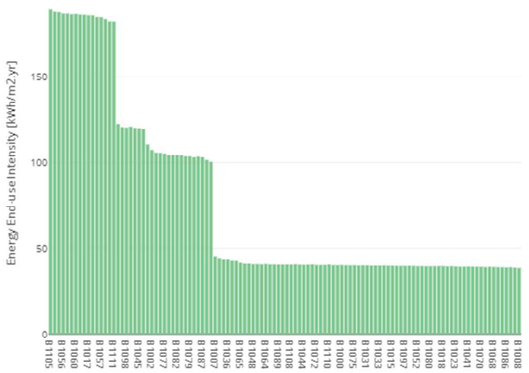
A - Space cooling demand only - SG database (BH1)



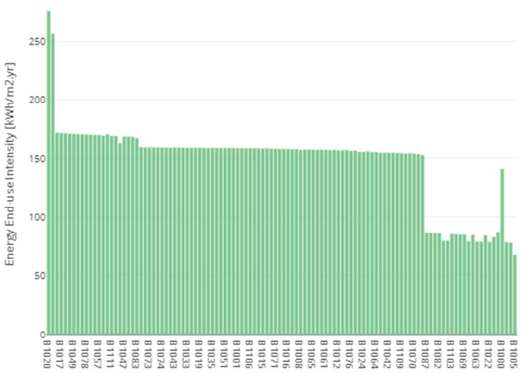
B - Space cooling demand only - BR database (BH1)



C - Electricity demand only - SG database (BH1)



D - Electricity demand only - BR database (BH1)



End-use space cooling demand
End-use electricity demand

Source: CEA. Compiled by the author.

When it comes to space cooling demands, both databases reached a similar maximum value of around 600 MWh/year. However, in terms of the behavior of each building, the values were different and the BR database reached the highest values when compared to the same buildings being characterized by SG. Variations in elements such as construction systems, colors of external walls, window-to-wall ratios and efficiency definitions of the cooling equipment in SG and BR could have impacted the results gathered with each database.

On the other hand, in addressing the electricity demand it is possible to notice that the BR graph far exceeded the maximum value reached by the SG one and the individual behavior of each building would follow the same path. A point worth emphasizing is the importance of electrical showers in Brazilian contexts, as previously mentioned. However, due to the current inability of CEA and its databases to process such data, they could not be included in the simulations. Their presence would have created a relevant impact on the electricity demand values.

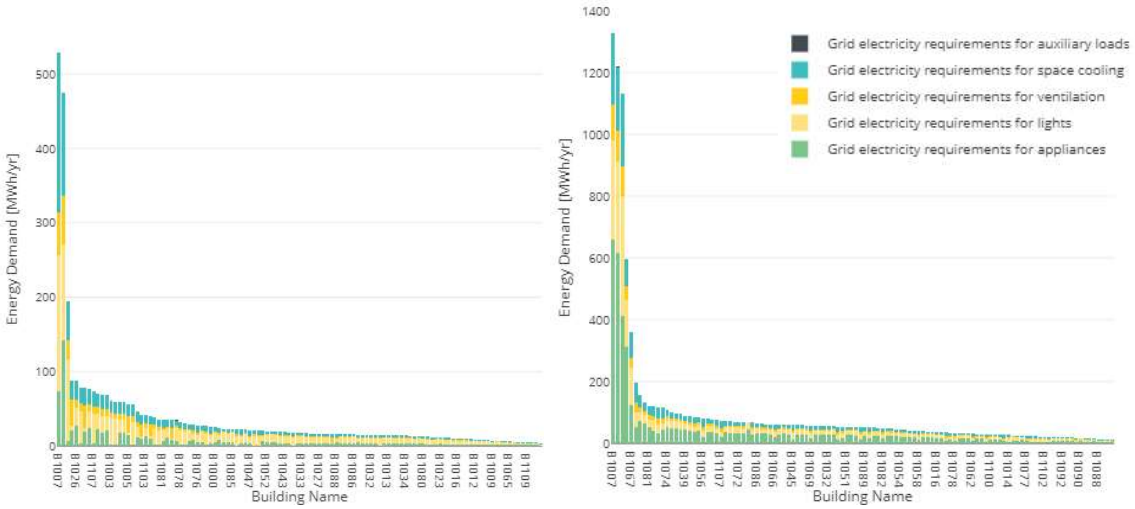
Moving on to the energy end-use intensity graphs, more specifically the ones addressing space cooling demands, the maximum values reached are relatively similar between both databases. On the other hand, the individual behavior of buildings presented important variations. Additionally, the buildings with the highest demands varied from database to database (B1105 for SG and B1020 using BR).

Finally, the electricity demand also showed a discrepancy in the maximum results reached by each database, albeit not as high as the ones from the electricity demand in the energy end-use graph. Another noticeable difference between SG and BR is that the former displayed the first 15 to 17 buildings with similar demands, followed by 7 with similar but lower values and so on, forming almost a "ladder-like" pattern, while BR clearly highlighted only 2 buildings as the highest demands in the chart, while the majority of others reached similar lower results. With that observation, it is clear that the SG chart was more homogeneous than the one generated by BR.

Energy Final Use and Energy Final Use Intensity

This section addresses the graphs mentioning where the electricity used by the studied buildings was mainly destined to, as well as its use intensity.

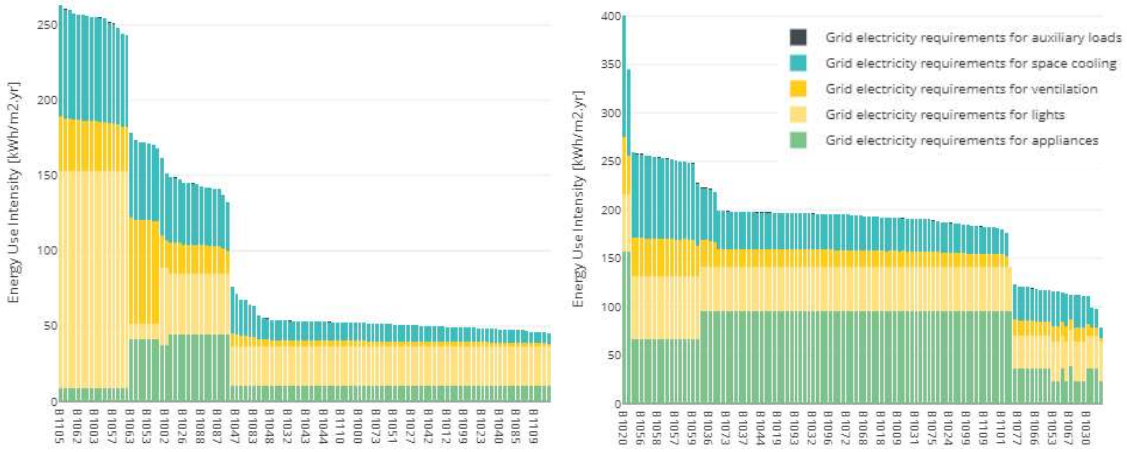
Image 60: Energy final use with SG (top) and BR (bottom)



Source: Generated by CEA.

When dealing with the final-use graphs, it is noticeable that SG generated results that pointed out space cooling, ventilation and artificial lighting as being the most energy demanding uses. BR showed similar predominances, but with two noticeable differences: the larger presence of electricity use for appliances in the graph and the highest values reached by the leading buildings (over 500 MWh/year with SG and over 1300 MWh/year with BR).

Image 61: Energy final use intensity with SG (top) and BR (bottom)



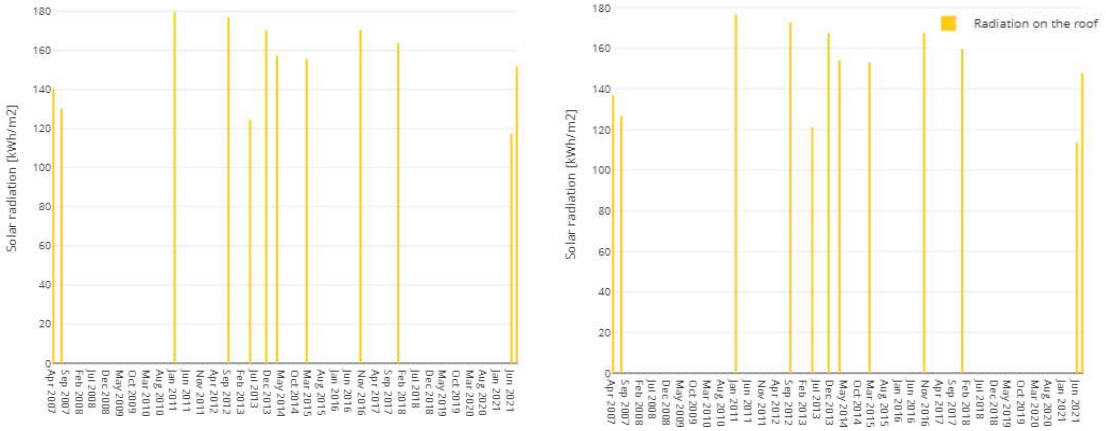
Source: Generated by CEA.

As for the use intensity, the maximum values reached once again proved to be different between databases, with a little over 250 kWh/m².yr with the SG database and around 400 kWh/m2.yr with the BR version. The most energy intensive uses were space cooling, ventilation and artificial lighting, in this order, albeit reaching different values depending on the analyzed database. Additionally, while the lighting requirements were higher with the SG database than with the BR one, the scenario reverses when it comes to the electricity requirements for appliances.

Solar Potential - Solar Radiation

The following charts describe the monthly solar radiation in BH1, normalized by surface area. Since both sets of simulations were run with the same weather file, the results are similar. The weather file used compiled climate-related data from 2007 to 2021, as shown below. In these simulations, incident radiation can be measured in vertical (walls) and horizontal (roof) planes, as well as in opaque and translucent surfaces. The four cardinal points - north, south, east and west - are considered as well. However, in order to focus the analysis on the data that are more useful for the studied area, the graphs addressed in this section only display the incident solar radiation on vertical surfaces (roofs).

Image 62: Solar radiation with SG (top) and BR (bottom)



Source: Generated by CEA.

In both sets of simulations, the roofs would receive from around 120 to 180 kWh/m² in radiation, with June-July (Brazilian winter) being the month with the lowest solar irradiance and January (Brazilian summer) as the month with the highest. Naturally, these values can vary considerably depending on factors such as the building height and its surrounding areas: for instance, photovoltaic panels installed in the roof of a

low-rise building surrounded by high constructions would achieve a less satisfactory performance compared to the same equipment being set on the roofs of tall multi-story buildings. In this studied area, a relevant part of the buildings are multi-story ones, but there are examples of low-rise buildings used as retail or single residences, for instance.

Regarding the software itself, it would be beneficial if the CEA could also consider the collateral points as well (Northeast, Northwest, Southeast and Southwest), since the urban fabric and building orientations can vary drastically from place to place.

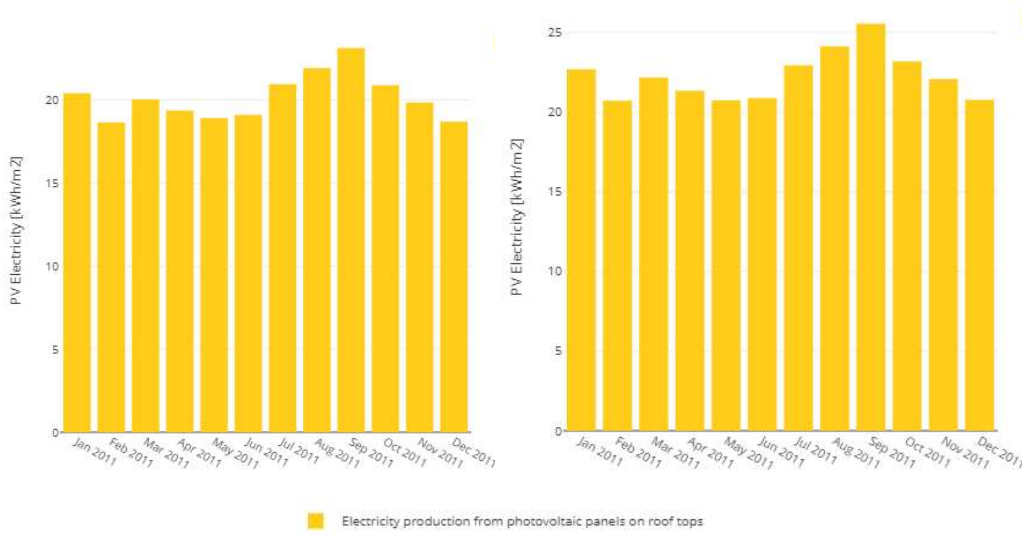
Technology Potentials

CEA presents in its settings the possibility of analyzing the potential of several types of technologies to produce electricity and/or thermal energy in urban scenarios: shallow geothermal, energy from water bodies, photovoltaic-thermal (PVT) panels, photovoltaic (PV) panels, heat from sewage and solar collectors. Focusing on the most relevant for the studied area, this section discusses the potential found for PVT and PV panels, as well as solar collectors.

Photovoltaic (PV) Potential

The following charts describe the monthly photovoltaic potential in the studied neighborhood, normalized by surface area. The result range between the SG and BR charts was not the same, but relatively similar, probably due to the same weather file being used in both cases and, at the same time, their respective PV equipment in the databases having slightly different technical specifications. In both simulations, only roof surfaces were chosen to be taken into account regarding electricity production from PV panels for the same reason as the previous topic: using vertical surfaces to gather solar radiation for electricity production is not a common practice in the studied area. It is worth mentioning that the year of 2011 was arbitrarily chosen by CEA to display the results and no other way to define a different time period was found on the software.

Image 63: PV electricity production with SG (top) and BR (bottom)



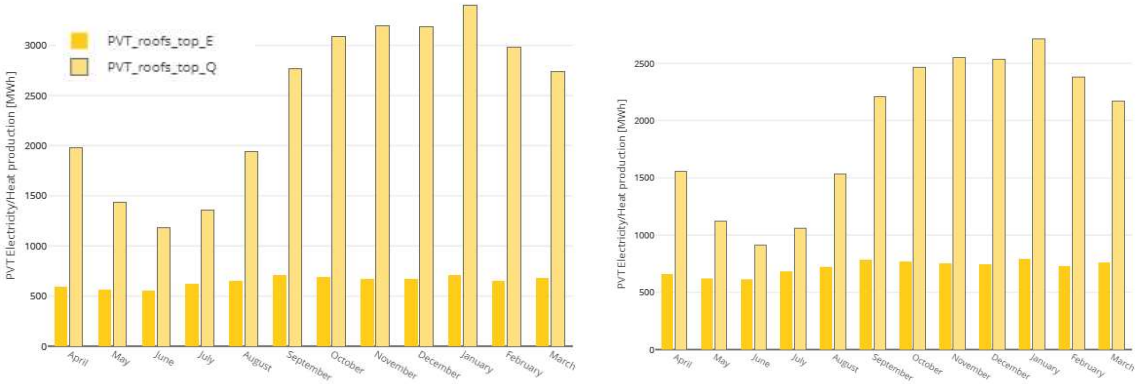
Source: Generated by CEA.

Both sets of charts pointed out that the months with higher electricity production during the year were September, August, July and January. The lowest values were found in February, May and June. In order to give context, the months of December to March represent Brazilian summer, while June to September are the winter season in the country. With that in mind, both charts indicate that there would be a considerable PV potential throughout the year in the studied area, even in what was supposed to be the coldest periods.

Photovoltaic-Thermal (PVT) Potential

The following charts display data regarding the potential for hybrid panel systems dedicated to generate both electricity and thermal energy. For the same reason as pointed out in the PV section, only roof surfaces were considered in both scenarios. In this case, the legend contrasts the electricity production from photovoltaic-thermal panels (PVT_roofs_top_E) and heat production from the same hybrid panels (PVT_roofs_top_Q) throughout the year, being measured in MWh.

Image 64: PVT electricity and thermal energy production with SG (top) and BR (bottom)



Source: Generated by CEA.

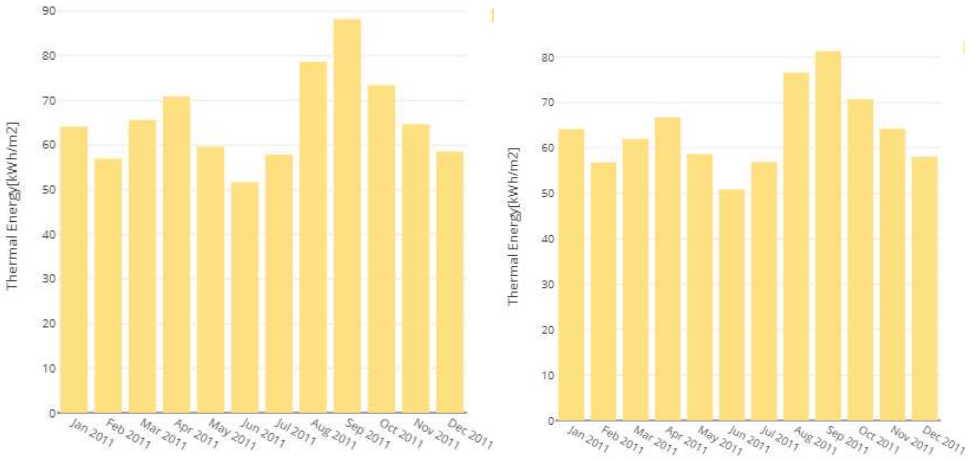
From a broader point of view, both charts displayed relatively close values throughout the year, with variations probably linked to the different settings of the PV options in each database. It is possible to notice that, in this case, the SG chart reached slightly higher values than the BR one: while the original database generated a graph with electricity production values ranging from around 500 MWh (May) to about 750 MWh (September) and thermal energy going from 1250 MWh (June) to over 3000 MWh (January), the recently created BR database produced a chart with electricity production values going from over 500 MWh (May) to around 800 MWh (September) and thermal energy reaching from over 800 MWh (June) to almost 3000 MWh (January). January and June represent part of the hottest and coldest seasons of the country, respectively, which tracks with the local reality.

Both sets of simulations show higher potential for a better performance for such hybrid panels to produce thermal energy rather than electricity, although the latter might be improved in the near future with the advancement of the technology. It is worth mentioning that, in the studied area, thermal energy of this nature is mainly used for water heating used during showers, for example.

Solar Collector Potential

The last two charts of BH1 compile data regarding the heat production from solar collectors, more specifically the evacuated-tube type (ET), installed on roof tops. The year defined by the CEA was 2011 and the graphs show monthly data normalized by surface area (kWh/m2).

Image 65: Heat production through solar collectors, with SG (left) and BR (right)



Source: Generated by CEA. Adapted by the author

Similar to the previous technologies addressed, the solar collector potential determined by the SG and BR simulations display similar values throughout most of the year, with a clear deviation during September, when the SG database would point out to a higher heat production. It is hypothesized, as mentioned before, that the divergences between the databases may occur due to the relatively different PV panels set in each one of them.

The highest production was detected in August and September, while the lowest result was found in June. As a brief piece of context, in the southern hemisphere (where Brazil is located) winter lasts precisely from June to September.

4.3.2 Céu Azul - Belo Horizonte (BH2)

Céu Azul is a predominantly residential area with low-rise buildings in the majority of its territory, with most of them being two-story buildings.

4.3.2.1 Input definitions

BH2 presents 94 buildings contained in a single city block, as illustrated in Image 66. This area used “Belo Horizonte-Pampulha” as its weather file, with a compilation of data between 2007 and 2021 just like BH1.

Image 66: BH2

Source: CEA. Modified by the author.

Similar to BH1, the input data in BH2 was also divided into the variables located on “Input Editor” and those on “Tools”, while the 3D geometry was taken from OpenStreetMap. The 9 input tables were set with the information shown in Table 19. The variables located in the “Tools” button were set with the same data as shown in Image 54.

Table 19: Input settings for BH2, with SG and BR databases ("Input Editor" tables).

	BH2_SG	BH2_BR
Zone	Taken from OpenStreetMap (No levels below ground)	Same settings as BH2_SG
Typology	Uses kept according to database and Open. **Standards:** SINGLE_RES and MULTI_RES set as STANDARD1; RETAIL set as STANDARD3.	Uses kept according to database and Open. **Standards:** SINGLE_RES and MULTI_RES set as STANDARD1 (exception: B1072 set as STANDARD15); RETAIL set as STANDARD5.
Architecture	Defined by the SG database, except for: TIGHTNESS (AS5 for all; AS6 for B1050 and B1051); ROOF (AS2 for all; AS1 for B1050 and B1051; and AS3 for B1067, B1068, B1029, B1028, B1027, B1026, B1025 and B1024); WALL (AS3 for all; AS1 for B1072, B1088 and B1000; and AS5 for B1069, B1024 and B1052); WINDOWS (AS1 for all).	Defined by the BR database, except for: TIGHTNESS (AS6 for B1050 and B1051); ROOF (AS1 for B1050 and B1051; and AS4 for B1067, B1068, B1029, B1028, B1027, B1026, B1025 and B1024); WALL (AS2 for all; AS5 for B1072, B1088 and B1000; and AS3 for B1069, B1024 and B1052); WINDOWS (AS3 for all; AS1 for B1069) and SHADING (AS7 for B1050 and AS6 for B1051).
Internal Loads	Defined by the SG database	Defined by the BR database
Indoor Comfort	Defined by the SG database	Defined by the BR database
Air-conditioning systems	Definitions, in order of appearance: SINGLE_RES and MULTI_RES (AS0 for all variables); RETAIL (HVAC_COOLING_AS2; HVAC_HEATING_AS0; HVAC_HOTWATER_AS0; HVAC_CONTROLLER_AS4 and HVAC_VENTILATION_AS1); B1040 (same definitions as RETAIL). Exceptions: B1042 and B1051 = AS0 for all variables	BR database - Definitions, in order of appearance: SINGLE_RES and MULTI_RES (AS0 for all variables); RETAIL (HVAC_COOLING_AS2; HVAC_HEATING_AS0; HVAC_HOTWATER_AS0; HVAC_CONTROLLER_AS2 and HVAC_VENTILATION_AS2). Exceptions: B1040 - assumption of having a split system made due to the building construction standard (HVAC_COOLING_AS2; HVAC_HEATING_AS0; HVAC_HOTWATER_AS0; HVAC_CONTROLLER_AS2 and HVAC_VENTILATION_AS2); B1042 (AS0 for all definitions); B1050 - assumption of having a split system made due to being classified as RETAIL, more specifically, a barber shop (HVAC_COOLING_AS2; HVAC_HEATING_AS0; HVAC_HOTWATER_AS0; HVAC_CONTROLLER_AS2 and HVAC_VENTILATION_AS2); B1051 (AS0 for all definitions).
Supply systems	Definitions, in order of appearance: SINGLE_RES and MULTI_RES (SUPPLY_COOLING_AS0;	Definitions from the BR database - Residential: SUPPLY_COOLING_AS0; SUPPLY_HOTWATER_AS0;

	SUPPLY_HOTWATER_AS0; SUPPLY_ELECTRICITY_AS1 and SUPPLY_HEATING_AS0); RETAIL (SUPPLY_COOLING_AS1; SUPPLY_HOTWATER_AS0; SUPPLY_ELECTRICITY_AS1 and SUPPLY_HEATING_AS0); B1040 (same definitions as RETAIL); B1042 and B1051 (AS0 for all variables).	SUPPLY_ELECTRICITY_AS1; SUPPLY_HEATING_AS0; RETAIL: SUPPLY_COOLING_AS2; SUPPLY_HOTWATER_AS0; SUPPLY_ELECTRICITY_AS1; SUPPLY_HEATING_AS0. Exceptions: B1040 and B1050 (same definitions as RETAIL); B1042 and B1051 (same definitions as the residential buildings)
Surroundings	Unchanged. Taken from OpenStreetMap	Unchanged. Taken from OpenStreetMap
Schedules	Defined by the SG database	Defined by the BR database

Source: Created by the author.

4.3.2.2 Output to be analyzed

As defined in chapter 3 (Methodology).

4.3.2.3 Results comparison

In BH2, 05 buildings were chosen as samples to be analyzed, as shown in Table 20.

Table 20: Sample buildings chosen for analysis in BH2

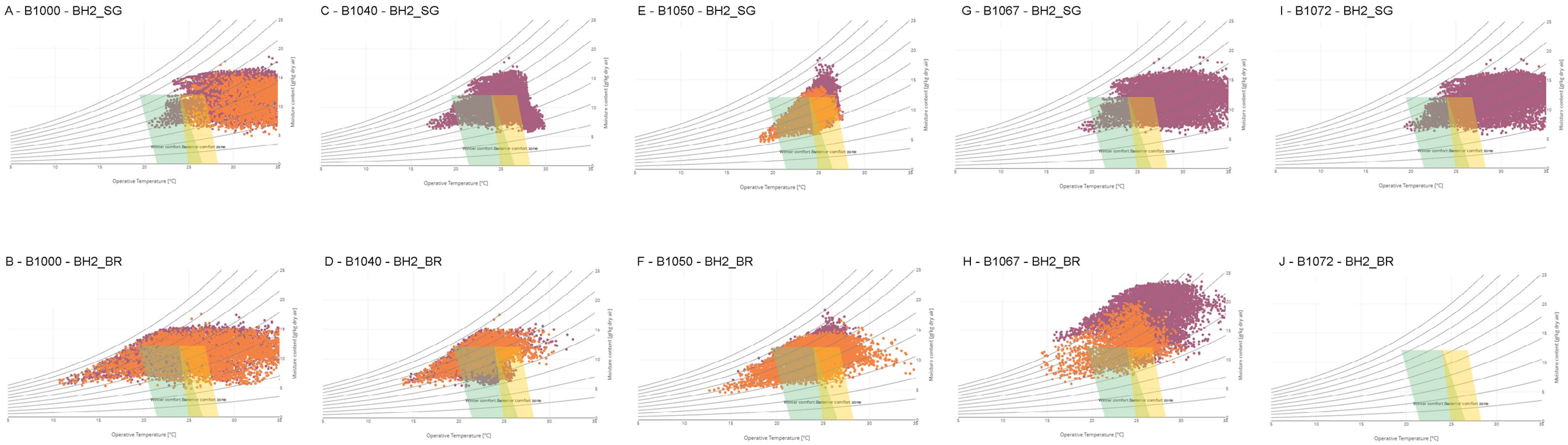
CODE	BRIEF DESCRIPTION
B1000	Set as SINGLE_RES without HVAC systems using both databases.
B1040	Set as SINGLE_RES with HVAC systems.
B1050	Set as RETAIL with HVAC systems.
B1067	Set as MULTI_RES without HVAC systems.
B1072	Set as SINGLE_RES without HVAC systems using both databases. However, with BR, said building was defined as a STANDARD15, destined to “atypical settlements”.

Source: Created by the author.

Comfort charts

The following page compiles the simulation results gathered using both SG and BR in BH2.

Image 67: Comfort charts of buildings in BH2 (Céu Azul/Belo Horizonte), with both databases.



Source: CEA. Compiled by the author.

Similar to the comfort charts in BH1, the ones generated for the chosen buildings in BH2 also presented differences amongst them, despite the fact that the same weather file was used with both databases. While all Brazilian scenarios presented both occupied and unoccupied hours, the majority of the ones generated by the Singaporean database (3 out of 5) displayed only occupied hours.

Except for chart E, both databases generated graphs that had the annual hours more scattered through the chart area. One example created by BR (chart H) presented some annual hours exiting the graph area, similarly to what happened in BH1.

However, the most significant result was signaled by charts I and J, linked to building B1072. This sample had some of its characteristics set differently depending on the database used: while it was defined as SINGLE_RES without HVAC systems in both cases, this building had different construction characteristics with the BR database. When setting the standards for the buildings, B1072 was defined as STANDARD15 ("Concrete and Masonry - Atypical Settlements"). This option, only available in the BR database, was created to represent a common type of building found not only in Brazil, but in other developing countries, and analyze CEA response to it. In both cases, no HVAC systems were active in this building. The absence of any results in chart J points to the lack of sensibility CEA possesses to analyze this type of social/urban reality, which deepens the distance between the tool and many Brazilian contexts.

Unlike the previous scenario, BH2 is characterized by a predominantly residential area with a high probability of a lack of any type of HVAC system in the vast majority of the buildings. In order to reduce the thermal discomfort due to heat, simpler and more affordable equipment such as floor fans and ceiling fans can be used. However, in the CEA version used in this research (3.34.2), these types of solutions cannot be considered in simulations.

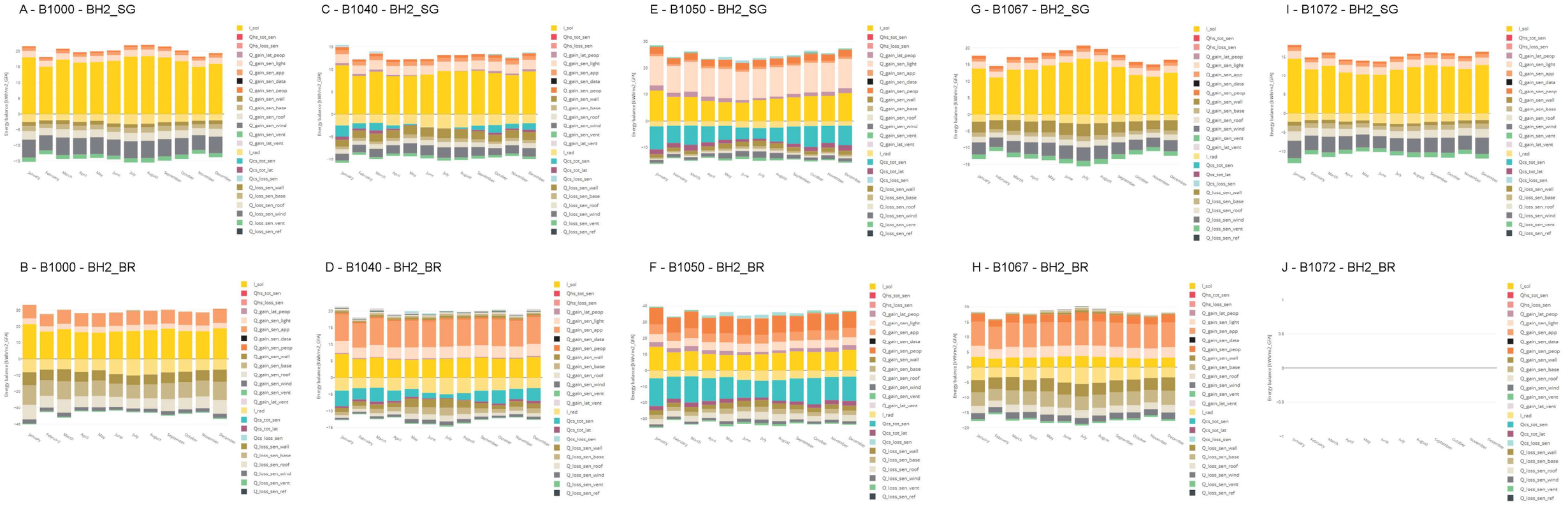
Energy Balance

The energy balance graphs of the buildings in BH2 are grouped in the following A3 page. The legend is the same as the one from BH1, shown in page 140.

Similar to the previous area, both SG and BR databases created graphs with similar variables being shown, albeit varying in terms of values. Apart from graphs D and H, all the other buildings pointed to "solar heat gain" as the most prevalent variable linked to gains. As for the losses, multiple variables were present, such as "total sensible heat involving cooling systems", "sensible heat loss through the base", "sensible heat loss through the roofs" and "sensible heat loss through windows". In some buildings, while the gains through lighting were more prominent in SG than in BR, appliances reached higher values in BR compared to SG.

Like BH1, the losses through windows reached more representative values with SG compared to BR in BH2, which was not expected due to the reasons mentioned in the previous area. And, once again, the absence of results in graph J points to the lack of sensibility of the software to atypical settlements.

Image 68: Energy balance of buildings in BH2 (Céu Azul/Belo Horizonte), with both databases.



Source: CEA. Compiled by the author.

Energy End-Use and Energy End-Use Intensity

The following A3 page contains the graphs from BH2 linked to energy end-use and energy end-use intensity. Unlike BH1, a region where the majority of buildings had some type of HVAC system put in place, most of buildings in BH2 were set without any cooling equipment due to its urban and economic characteristics, as well as the current inability of CEA to consider more affordable options, such as floor fans. Additionally, the absence of a survey regarding the presence of such equipment in the analyzed buildings also impacted this output. This factor had a direct influence on the following graphs. In total, 2 of 94 buildings had some type of HVAC system.

One of the main differences between databases in the energy end-use graph with information about cooling demands (Image 69A and B) is the range values reached by the two buildings set with HVAC systems (B1050 and B1040): with SG, they reached far lower values when compared to the BR chart. As a similarity, B1050 was the most demanding building in terms of energy directed to cooling in both charts.

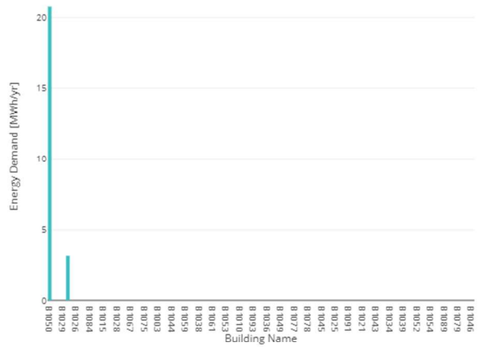
As for the electricity demand (Image 69C and D), not only the maximum values reached were considerably different from SG to BR (the latter reaching the highest numbers), but also the dominance of the most energy demanding building compared to the other simulated constructions is significantly different: with SG, the building with the highest demand clearly stands out from the rest, while with BR the first three buildings are relatively close to each other, demand-wise.

Discussing cooling demands in the energy end-use intensity graphs, the maximum values reached were once again divergent between databases, with BR reaching the highest values. As for the electricity demand, this difference was considerably smaller and both SG and BR graphs followed a similar pattern where two buildings would stand out while the rest would reach close levels of energy demand. On the other hand, the values reached by the buildings would be considerably different between databases. Being able to include more affordable cooling options such as fans was especially needed in this region, since it is less economically developed than BH1.

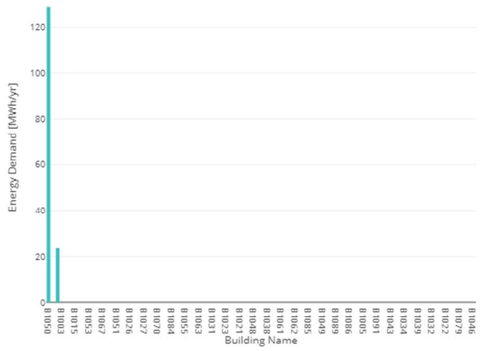
A crucial point to highlight is that B1072, the building set as an atypical settlement and which had not generated neither comfort charts nor energy balance graphs, showed up in this energy end-use graph (electricity demand only). However, B1072 is not featured in the cooling demand graph since it does not possess any HVAC systems set in its simulations.

Image 69: Energy end-use graphs of BH2 (Céu Azul/Belo Horizonte), with both databases.

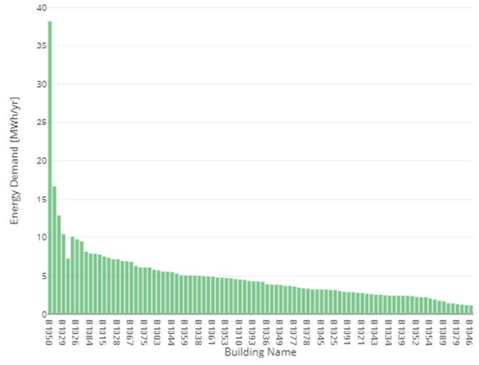
A - Space cooling demand only - SG database (BH2)



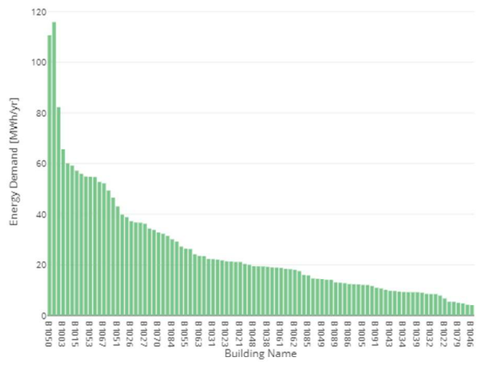
B - Space cooling demand only - BR database (BH2)



C -Electricity demand only - SG database (BH2)



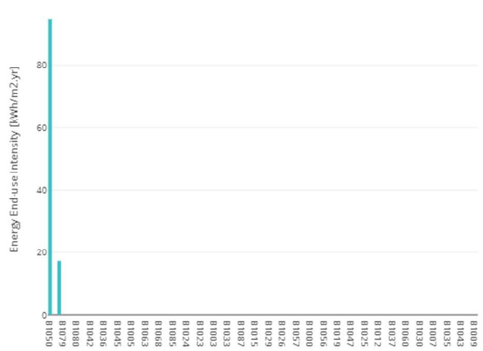
D - Electricity demand only - BR database (BH2)



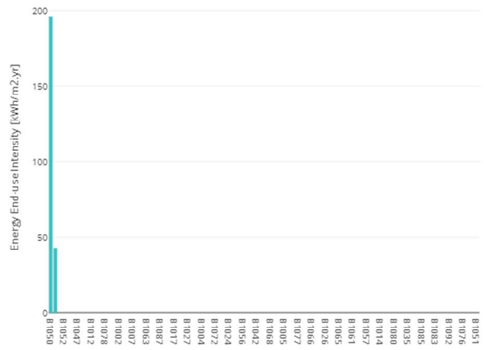
End-use space cooling demand
End-use electricity demand

Image 70: Energy end-use intensity graphs of BH2 (Céu Azul/Belo Horizonte), with both databases.

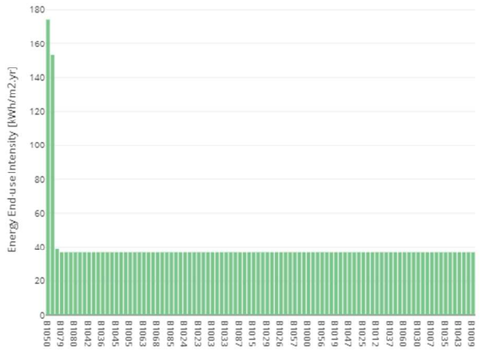
A - Space cooling demand only - SG database (BH2)



B - Space cooling demand only - BR database (BH2)



C - Electricity demand only - SG database (BH2)



D - Electricity demand only - BR database (BH2)

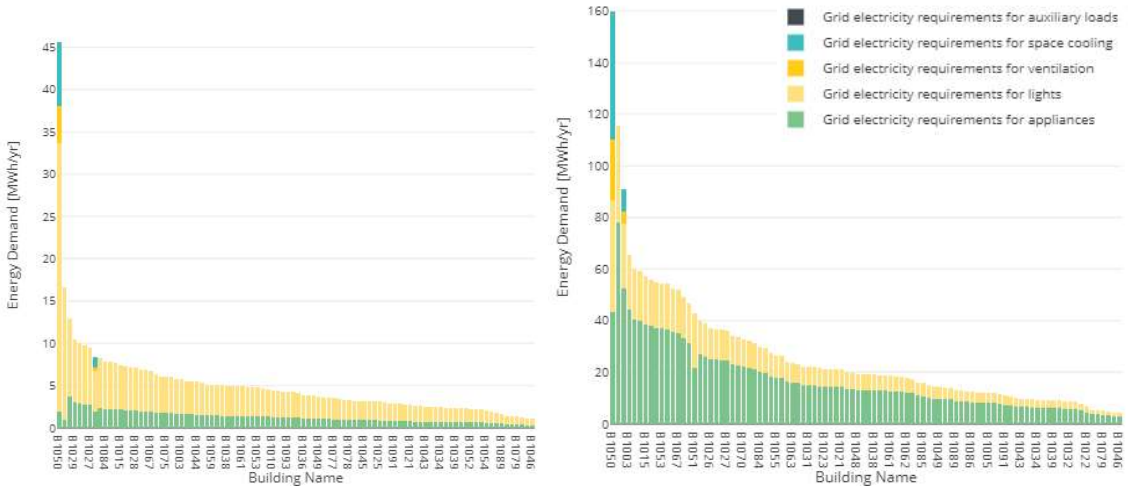
End-use space cooling demand
End-use electricity demand

Source: CEA. Compiled by the author.

Energy Final Use and Energy Final Use Intensity

In terms of the energy final use, both graphs show a predominance of two specific uses: lighting and appliances, with B1050 and B1051 leading the SG graph and B1050 and B1056 leading the BR one. Once again, the Brazilian database generated a graph in which the simulated buildings reached higher values than those in the chart created with the Singaporean database.

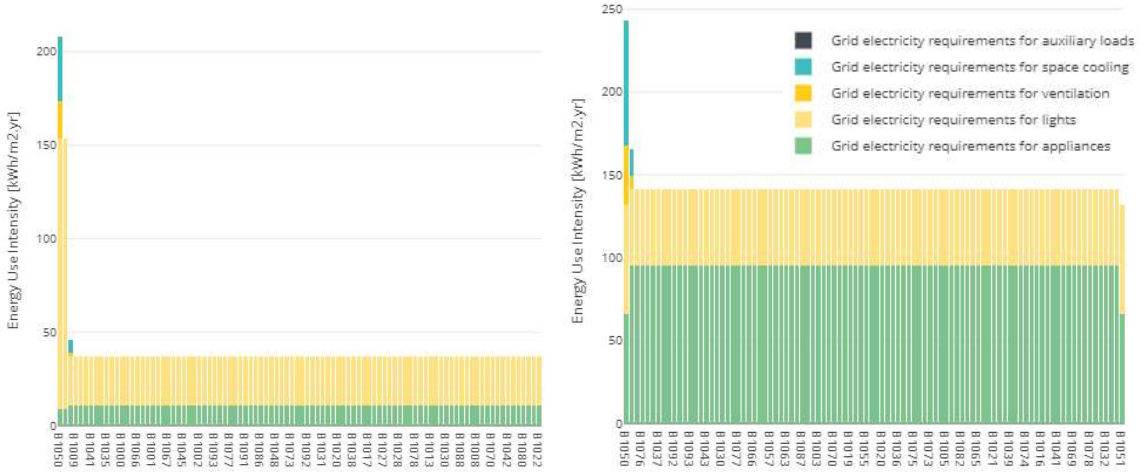
Image 71: Energy final use with SG (top) and BR (bottom)



Source: Generated by CEA.

The final use intensity in both graphs displayed slight contrasts in terms of values, albeit following a similar logic behind the variations among buildings, with two of them having higher demands than the others by a long margin (in this case, B1050 and B1051 with the SG database and B1050 and B1040 with the BR one). The major uses in both graphs were lighting and appliances, although the leading use changed depending on the database: with SG, the leading use was lighting, followed by appliances; while BR showed a predominance of electricity requirements for appliances and, then, for lighting. Still with the BR database, B1072 (atypical settlement) presented no results for cooling and a predominance of electricity requirements for appliances, followed by lighting.

Image 72: Energy final use intensity with SG (top) and BR (bottom)

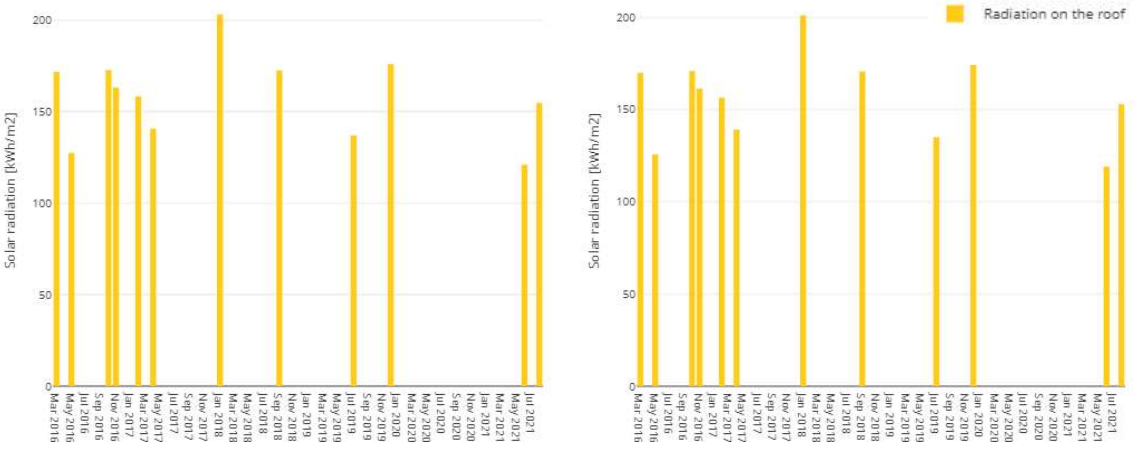


Source: Generated by CEA.

Solar Potential - Solar Radiation

In this area, the weather file used compiled data from 2007 to 2021, just like BH1. Both graphs were normalized by surface area and display monthly results, focusing only on the incident radiation on roofs.

Image 73: Solar radiation with SG (top) and BR (bottom)



Source: Generated by CEA.

Similar to what happened in BH1, the graphs generated with both databases presented very similar results as the weather file used in each one was identical. However, in this set of simulations, CEA displayed data from March 2016 to August 2021, once again being unclear to the user if it would be possible to set within the software a different timeframe.

In both graphs, the solar radiation varied from around 120 kWh/m² (June, 2021) to about 200 kWh/m2 (January, 2018). Unlike BH1, a central area with higher urban density and several multi-story buildings, BH2 is a predominantly residential neighborhood with the majority of buildings having two floors above ground level. For this reason and also being aware that other factors might need to be included in this analysis, it is relevant to consider that in areas like these the solar potential could be higher due to the lack of shading by high-rise buildings, an element that would directly impact the panels performance.

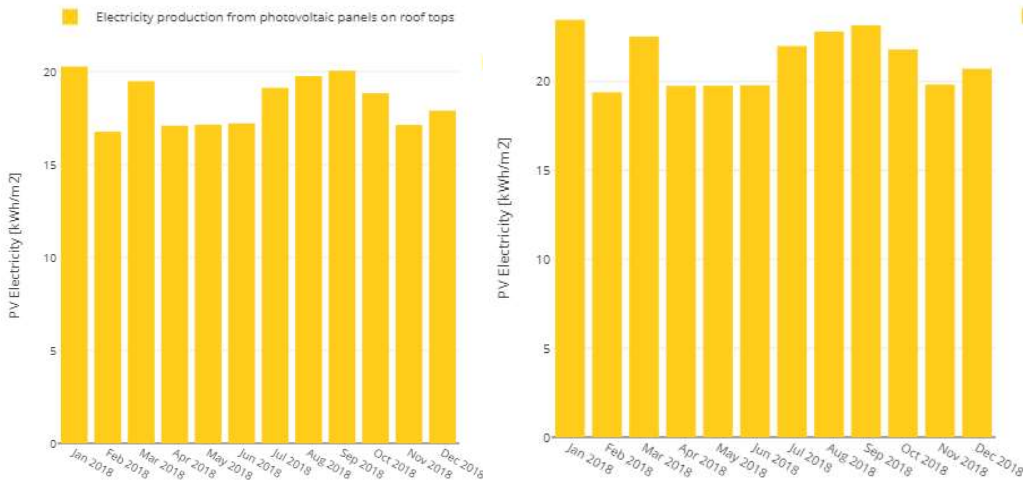
Technology Potentials

Following the same logic as in BH1, the three technologies to be discussed are PVs, PVTs and solar collectors.

Photovoltaic (PV) Potential

As illustrated by Image 74 and despite using the same weather file during the simulations, the graph generated with the SG database presented contrasts in comparison to the one created with the BR database in terms of values. These graphs once again focus on the electricity produced monthly from PV panels installed only on roof tops. Such data was also normalized by surface area and, in this case, CEA displayed results gathered in 2018.

Image 74: PV electricity production with SG (top) and BR (bottom)



Source: Generated by CEA.

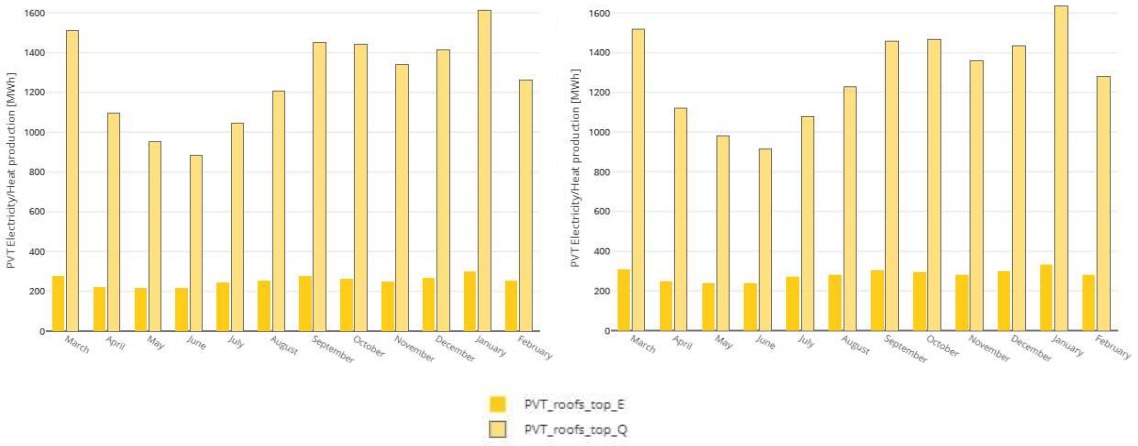
The graph based on the "Belo Horizonte-Pampulha" weather file and SG database shows that January was the month with the highest electricity production, followed by

September. On the other hand, the months with the lowest electricity production would be February and April. The graph created with the BR database (bottom) and the same weather file reinforced January and September as the months with the most relevant electricity production, while pointing to February and April as the months with the lowest production. May and June reached almost the same potential.

Photovoltaic-Thermal (PVT) Potential

In terms of the potential for hybrid panel systems in the area, the graphs obtained with both databases presented very similar results to each other, which is relevant.

Image 75: PVT electricity and thermal energy production with SG (top) and BR (bottom).



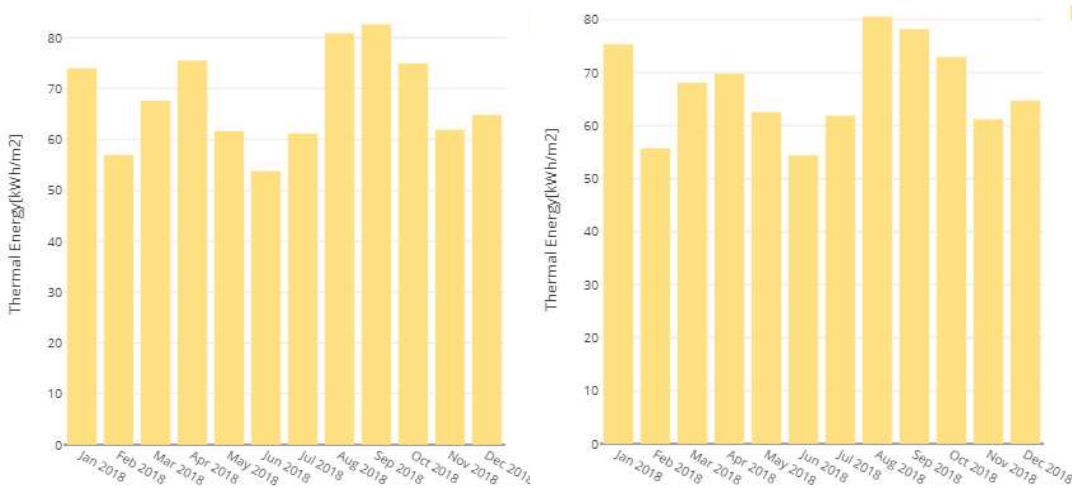
Source: Generated by CEA.

As a quantitative example between databases, SG produced a graph in which the highest thermal production was achieved in January (1.614,44 MWh) and the highest electricity production peaked in the same month (298,53 MWh). As for the lowest values, June reached 882,91 MWh in thermal energy and May got up to 214,91 MWh in electricity. The graph generated with the BR database pointed to January reaching 1.637,71 MWh in thermal production and 332,9 MWh in electricity, while June presented 913,61 MWh in heat and May hit 238,47 MWh in electricity.

Solar Collector Potential

The following charts display the potential for evacuated-tube collectors installed on roof tops and with data from 2018, as defined by the software.

Image 76: Heat production through solar collectors, with SG (left) and BR (right)



Source: Generated by CEA.

In general, the graphs obtained with both databases presented relatively similar results again, quantitative speaking, and the months with higher and lower thermal productions were alike. With the SG database, September was the month with the highest thermal energy production and June reached the lowest. As for the BR database, August peaked with the highest production while June was featured once again as the month with the lowest value of thermal energy produced. Similar results in the analyzed technologies could sign that these functionalities in the software would be ready to be used immediately in other Brazilian scenarios.

4.3.3 Downtown Matozinhos (MTZ1)

Downtown Matozinhos is, like most of the city itself, composed of low-rise buildings (1 to 3 floors), with a few taller exceptions. For being the central area, MTZ1 presents several building uses, such as residences, retail spaces, public buildings, churches, educational institutions, among others.

4.3.3.1 Input definitions

MTZ1 presents 101 buildings spread among 04 blocks (Image 77). For this area, the weather file “Belo Horizonte-Carlos Prates”, with data from 2007 to 2021, was used.

Image 77: MTZ1

Source: CEA. Modified by the author.

The input data followed the same logic as the previous areas. Table 21 summarizes the information inserted in each one of the 09 tables in the “Input Editor” button.

Table 21: Input settings for MTZ1, with SG and BR databases (“Input Editor” tables).

	MTZ1_SG	MTZ1_BR
Zone	Taken from OpenStreetMap, with no floors below ground being adopted. **Alterations - "floors_ag":** B1062 (3 floors); B1063 (2); B1072 (2); B1100 (2); B1096 (2); B1095 (2); B1094 (2); B1091 (4); B1022 (6); B1015 (2); B1013 (2); B1011 (2); B1000 (2); B1044 (2); B1048 (2); B1019 (3); B1037 (2); B1053 (2); B1057 (2); B1055 (2); B1054 (2) and B1079 (2). **Height of each floor = 3 meters**	Same settings as MTZ1_SG

Typology	Open + SG database. **Exceptions:** B1062 (0.66 OFFICE; 0.34 RETAIL); B1063 (0.5 RETAIL; 0.5 SINGLE_RES); B1072 (1- RETAIL); B1100 (0.5 RETAIL; 0.5 SINGLE_RES); B1096 (1- OFFICE); B1095 (1- RETAIL); B1094 (1- RETAIL); B1091 (0.75 MULTI_RES; 0.25 RETAIL); B1090 (Real-life church set as SCHOOL, 1); B1022 (0.83 MULTI_RES; 0.17 RETAIL); B1015 (0.5 RETAIL; 0.5 SINGLE_RES); B1013 (1- SINGLE_RES); B1011 (1- RETAIL); B1000 (1- RETAIL); B1048 (0.5 RETAIL; 0.5 SINGLE_RES); B1019 (Real-life bank set as OFFICE, 1); B1037 (1- RETAIL); B1053 (1- RETAIL); B1057 (1- SINGLE_RES); B1055 (0.5 RETAIL; 0.5 SINGLE_RES); B1054 (1- SCHOOL) and B1079 (1- SINGLE_RES). Use changes: B1054 (real-life church set as SCHOOL). **STANDARDS:** SINGLE_RES and MULTI_RES set as STANDARD1; RETAIL, SCHOOL, OFFICE and UNIVERSITY set as STANDARD3; PARKING set as STANDARD4. B1022 set as STANDARD2 and B1048 set as STANDARD4.	Open + BR database. **Exceptions:** same definitions as the previous scenario (MTZ1_SG). **Use adaptations:** B1054 (real-life church set as PR_SCHOOL); B1000 (MARKET); SCHOOL and UNIVERSITY set as PR_SCHOOL; PARKING set as RETAIL. **STANDARDS:** SINGLE_RES and MULTI_RES set as STANDARD1; RETAIL and MARKET set as STANDARD5; PR_SCHOOL set as STANDARD13; OFFICE set as STANDARD7. Others: B1022 set as STANDARD3; B1062 set as STANDARD9; B1079 set as STANDARD15.
Architecture	Mainly defined by the SG database after the alterations on "Typology". **SETTINGS - All buildings:** CONSTRUCTION_AS2; TIGHTNESS_AS5 (exceptions: B1079 and B1098 - AS6); ROOF_AS2 (exceptions: B1000, B1037 and B1044 - AS3; B1062 - AS1); SHADING_AS0 (exception: B1096 - AS2); WALL_AS3 (exceptions: B1100, B1022, B1044, B1048, B1037 - AS5; B1098 - AS1; B1079 - AS2); WALL_AS3 (partition); FLOOR_AS1; FLOOR_AS1 (base); WINDOW_AS1 (exception: B1022 - AS8).	Mainly defined by the BR database after the alterations on "Typology". **SETTINGS - All buildings:** CONSTRUCTION_AS2; TIGHTNESS_AS5 (exceptions: B1079 and B1098 - AS6); ROOF_AS2 (exceptions: B1000, B1037 and B1044 - AS4; B1062 - AS1); SHADING_AS3 (exceptions: B1055 - AS4; B1072 - AS7; B1098 and B1037 - AS6; B1096 - AS1; B1062 - AS0); WALL_AS2 (exceptions: B1100, B1022, B1044, B1048, B1037 - AS3; B1098 - AS5; B1079 - AS6); WALL (partition) - BR database (exception: B1079 - AS6); FLOOR_AS1; FLOOR_AS1 (base); WINDOW_AS3 (exception: B1022 - AS2; B1062 - AS5; B1011 - AS6; B1013 - AS1).
Internal Loads	Defined by the SG database.	Defined by the BR database.
Indoor Comfort	Defined by the SG database.	Defined by the BR database.
Air-conditioning systems	**All buildings:** HVAC_COOLING_AS0; HVAC_HEATING_AS0;	**All buildings:** HVAC_COOLING_AS0; HVAC_HEATING_AS0; HVAC_HOTWATER_AS0;

	HVAC_HOTWATER_AS0; HVAC_CONTROLLER_AS0; HVAC_VENTILATION_AS0. Buildings set with HVAC systems (B1063, B1011, B1072, B1100, B1095, B1094, B1091, B1022, B1000, B1019, B1053): HVAC_COOLING_AS2; HVAC_HEATING_AS0; HVAC_HOTWATER_AS0; HVAC_CONTROLLER_AS4; HVAC_VENTILATION_AS1	HVAC_CONTROLLER_AS0; HVAC_VENTILATION_AS0. Buildings set with HVAC systems: COOLING [B1063, B1072, B1100, B1095, B1094, B1091, B1022 and B1000 - AS1; B1019 - AS3 (assumption); B1011 and B1053 - AS2 (assumption)]; HVAC_HEATING_AS0; HVAC_HOTWATER_AS0; HVAC_CONTROLLER_AS2; HVAC_VENTILATION_AS2.
Supply systems	**All buildings:** SUPPLY_COOLING_AS0; SUPPLY_HOTWATER_AS0; SUPPLY_ELECTRICITY_AS1; SUPPLY_HEATING_AS0. Buildings set with HVAC systems (B1063, B1011, B1072, B1100, B1095, B1094, B1091, B1022, B1000, B1019, B1053): SUPPLY_COOLING_AS1; SUPPLY_HOTWATER_AS0; SUPPLY_ELECTRICITY_AS1; SUPPLY_HEATING_AS0	**All buildings:** SUPPLY_COOLING_AS0; SUPPLY_HOTWATER_AS0; SUPPLY_ELECTRICITY_AS1; SUPPLY_HEATING_AS0. Buildings with HVAC systems: SUPPLY_COOLING_AS1 (B1063, B1072, B1100, B1095, B1094, B1091, B1022 and B1000) or SUPPLY_COOLING_AS2 (B1011 and B1053 - assumption) or SUPPLY_COOLING_AS3 (B1019 - assumption); SUPPLY_HOTWATER_AS0; SUPPLY_ELECTRICITY_AS1; SUPPLY_HEATING_AS0.
Surroundings	Unchanged. Taken from OpenStreetMap.	Unchanged. Taken from OpenStreetMap.
Schedules	Defined by the SG database.	Defined by the BR database.

Source: Created by the author.

4.3.3.2 Output to be analyzed

As defined in chapter 3 (Methodology).

4.3.3.3 Results comparison

In this last scenario, 06 buildings were chosen to be discussed, as listed in Table 22. The use adaptation, such as the church set as a school, was done in regards to the available schedule options in each database, in which the closest occupation pattern would be chosen to characterize the mentioned building.

Table 22: Sample buildings chosen for analysis in MTZ1

CODE	BRIEF DESCRIPTION
B1000	A real-life supermarket set as MARKET with HVAC systems using both databases.
B1013	Set as SINGLE_RES without HVAC systems.
B1022	Set as MULTI_RES/RETAIL with HVAC systems.
B1062	Set as OFFICE without HVAC systems.
B1090	A real-life church set as SCHOOL with SG and PR_SCHOOL with BR, both without HVAC systems.
B1095	Set as RETAIL with HVAC system.

Source: Created by the author.

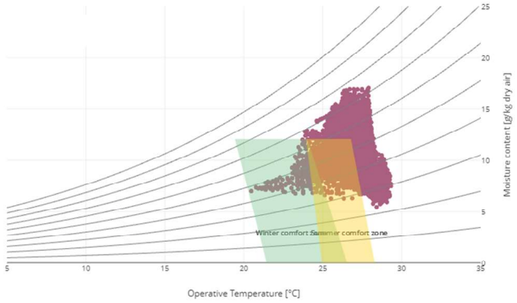
The EPW used in this area was one from Belo Horizonte, as previously mentioned, due to the lack of weather files made specifically for Matozinhos.

Comfort charts

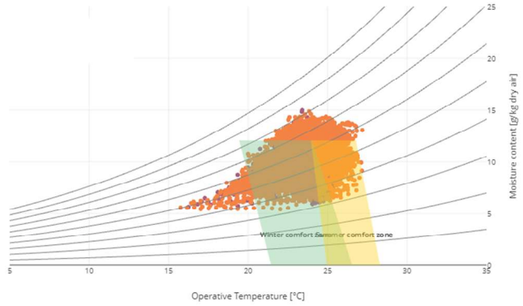
Generally speaking, all the charts displayed in the following page presented differences depending on the database used, as seen in the previous two analyzed urban areas.

Image 78: Comfort charts of buildings in MTZ1 (downtown Matozinhos), with both databases.

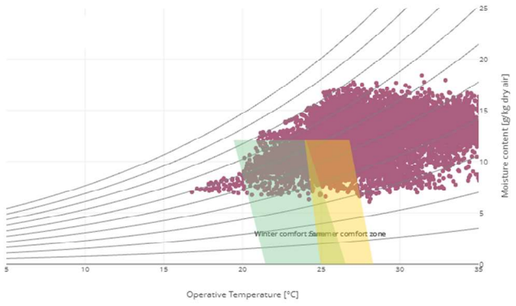
A - B1000 - MTZ1_SG



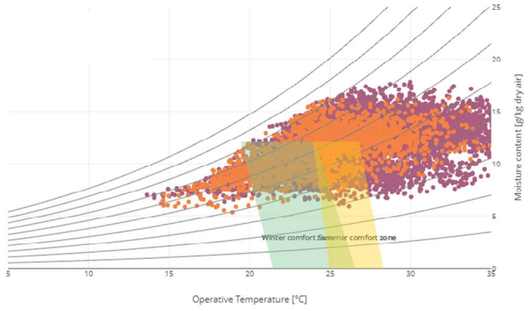
B - B1000 - MTZ1_BR



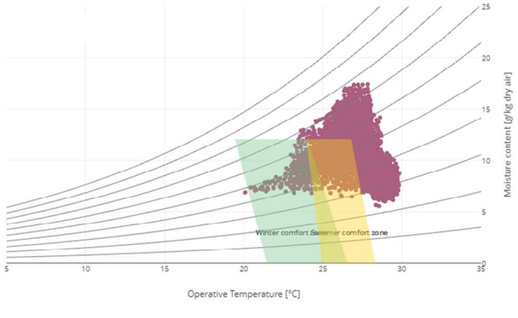
C - B1013 - MTZ1_SG



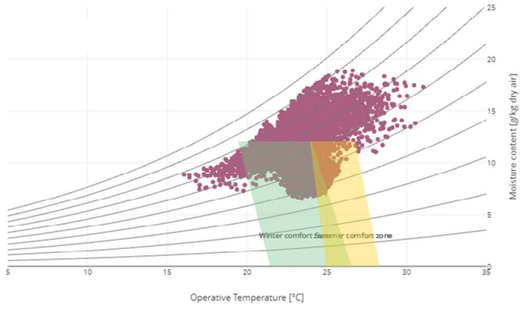
D - B1013 - MTZ1_BR



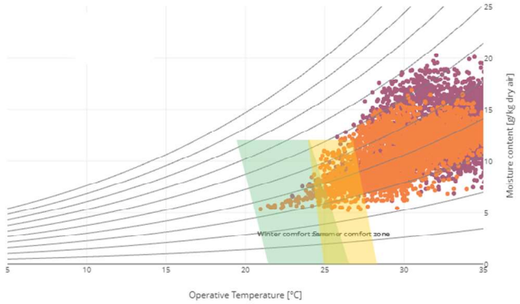
E - B1022 - MTZ1_SG



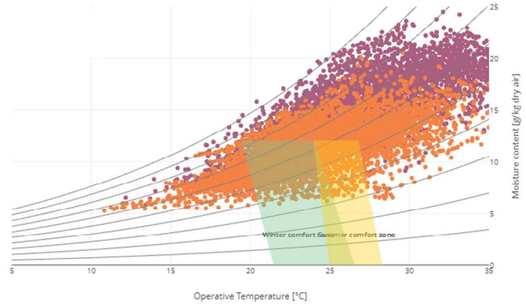
F - B1022 - MTZ1_BR



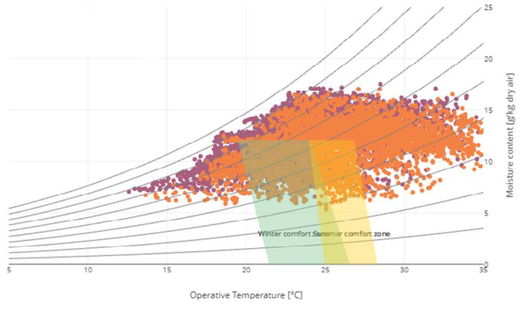
G - B1062 - MTZ1_SG



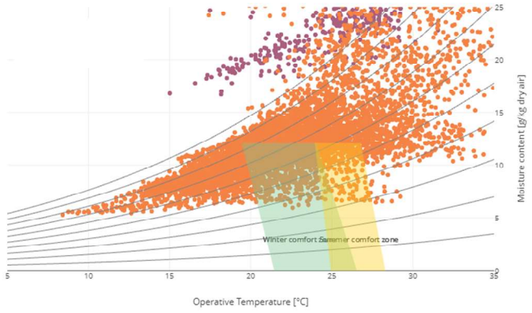
H - B1062 - MTZ1_BR



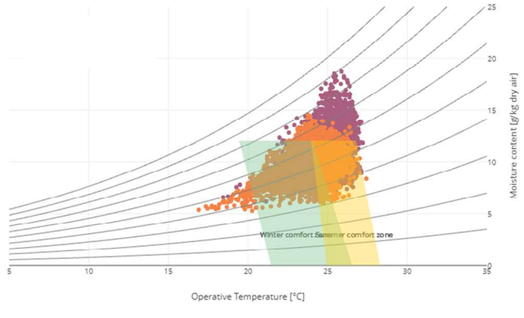
I - B1090 - MTZ1_SG



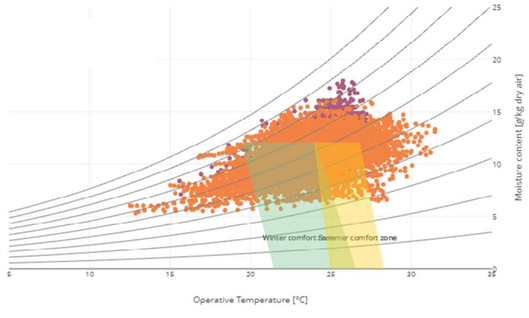
J- B1090 - MTZ1_BR



K - B1095 - MTZ1_SG



L - B1095 - MTZ1_BR



Source: CEA. Compiled by the author.

- Occupied hours summer
- Unoccupied hours summer

The pattern followed by the charts from each database is relatively similar when discussing some specific buildings, apart from B1090 (charts I and J) which diverges more prominently than the others. In some cases, the annual hours are more concentrated in the central areas of the charts and in some others, they are more dispersed. Since the weather file was the same for both SG and BR simulations, the reason behind the deviations of relevant proportions is unknown. A question regarding the possibility of the differences between databases, such as their use schedules, being able to affect their respective results was raised. However, no clear explanation for this situation was found in the present research. There were cases in which only occupied hours were displayed and others where both occupied and unoccupied hours were considered.

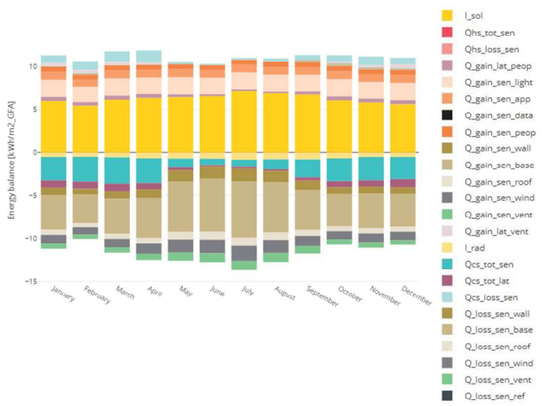
As anomalies, the behavior of the chart from B1090 with the Brazilian database is noticeable, where some annual hours are shown outside of the chart, similar to the previously studied areas. B1090 represented a real-life church set as SCHOOL with the SG database and PR_SCHOOL with the BR one, both without HVAC systems. The reason for such definition was due to the inexistence, up to this moment, of a specific schedule for churches in the BR database. The anomaly in such a graph raised a hypothesis initially connecting said behavior to divergent schedules between databases. However, since SG also provided a school schedule for B1090 and its chart did not present the same outcome, this hypothesis was discarded and another reason is yet to be found. It is relevant to emphasize that the schedules in the Brazilian database were based on available national regulations appropriately chosen for each use, such as INI-C.

Energy Balance

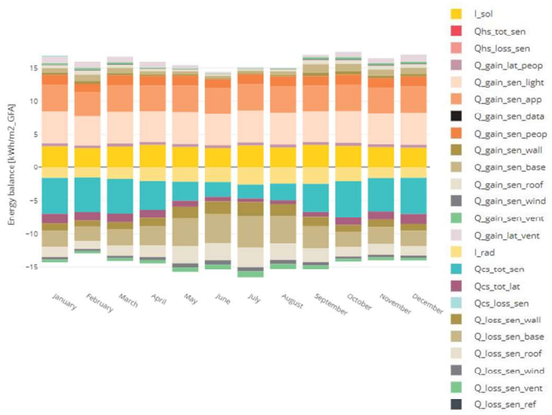
The following A3 page compiles the graphs from every building sample in MTZ1, the same ones discussed in the previous section.

Image 79: Energy balance of buildings in MTZ1 (downtown Matozinhos), with both databases.

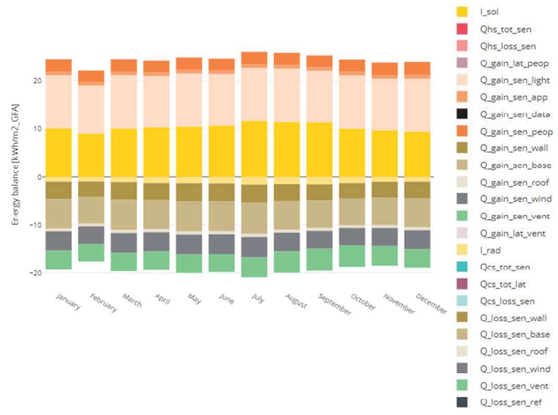
A - B1000 - MTZ1_SG



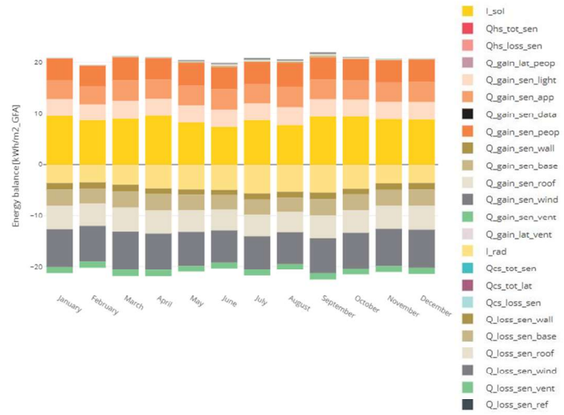
B - B1000 - MTZ1_BR



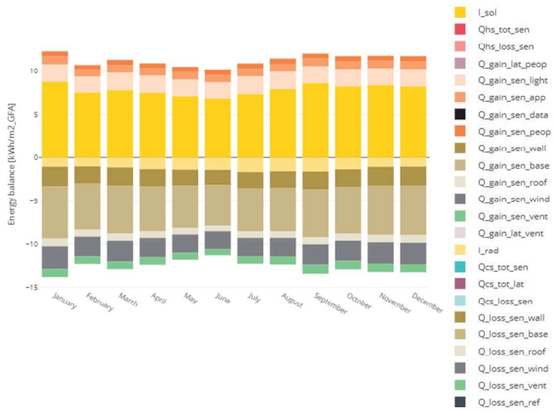
G - B1062 - MTZ1_SG



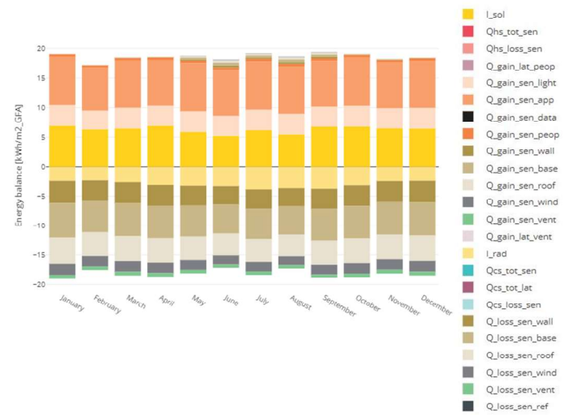
H - B1062 - MTZ1_BR



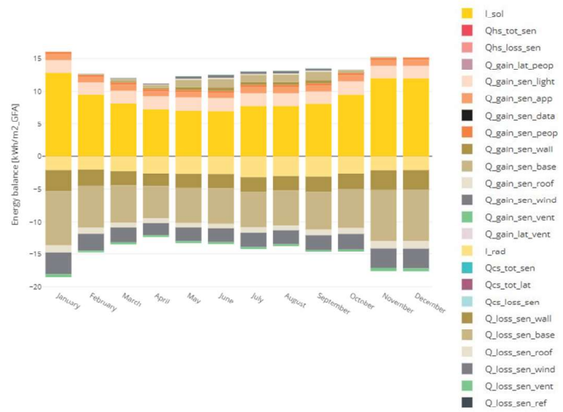
C - B1013 - MTZ1_SG



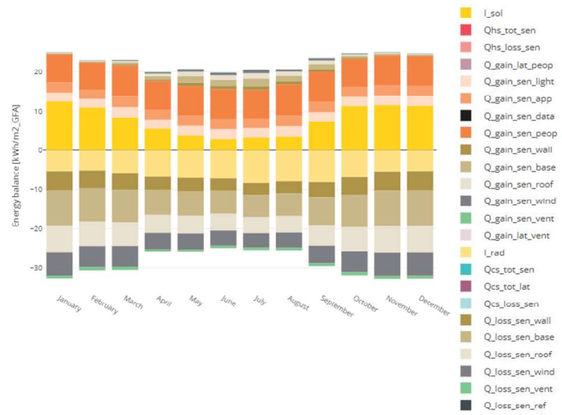
D - B1013 - MTZ1_BR



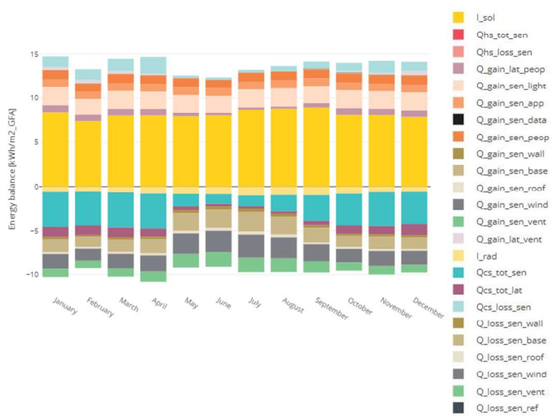
I - B1090 - MTZ1_SG



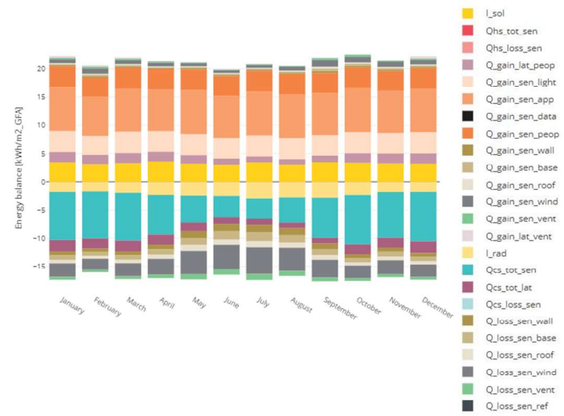
J - B1090 - MTZ1_BR



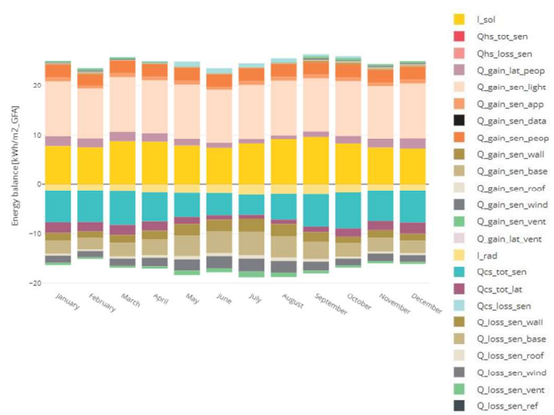
E - B1022 - MTZ1_SG



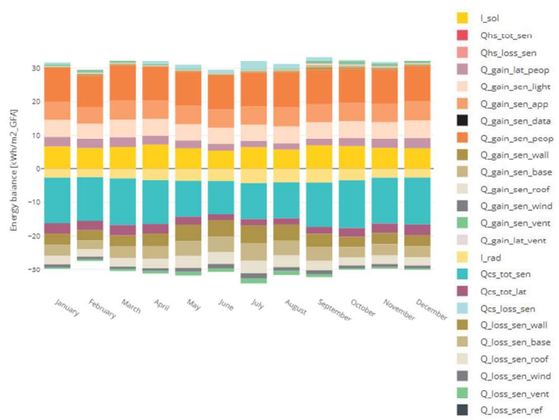
F - B1022 - MTZ1_BR



K - B1095 - MTZ1_SG



L - B1095 - MTZ1_BR



Source: CEA. Compiled by the author.

A similar pattern found in BH1 and BH2 is also present in MTZ1, in which all graphs display similar variables for each building, but show variations in terms of the values obtained by them. It was initially considered that these quantitative divergences might be influenced by different technical specifications in each database, regarding the thermal properties of each construction element that was used to characterize the buildings. However, since the focus of the present research is to analyze the software performance in Brazilian scenarios rather than investigate the absolute values of each simulated building individually, no proof related to this situation was found.

Generally speaking, the most predominant variable linked to gains in the majority of cases was "solar heat gain", while "sensible heat loss through roofs" and "total sensible heat involving cooling systems" represented the most present types of losses in both scenarios.

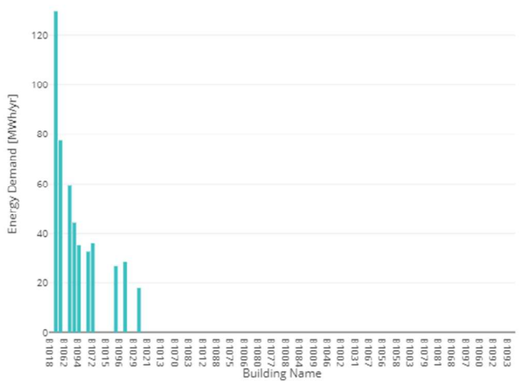
From a quantitative point of view, although SG and BR databases generated energy balance graphs with variables reaching different values, the maximum numbers each set of graphs displayed were not dramatically far from each other: while the gains collectively reached up to 20 kWh/m²_GFA (gross floor area), the losses went up to around -20 kWh/m²_GFA collectively.

Energy End-Use and Energy End-Use Intensity

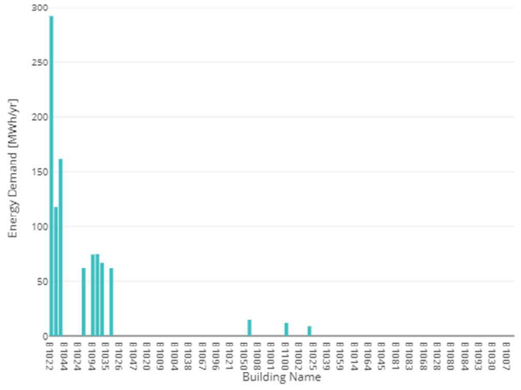
Compared to the two previous areas, MTZ1 was the second with the highest number of buildings with any HVAC settings in place in the present work - BH1 being the first by a long margin and BH2, the third. In each set of simulations in the present area, only 11 of the 101 buildings had active HVAC systems.

Image 80: Energy end-use graphs of MTZ1 (downtown Matozinhos), with both databases.

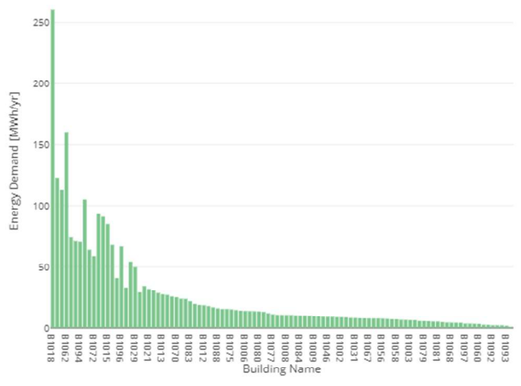
A - Space cooling demand only - SG database (MTZ1)



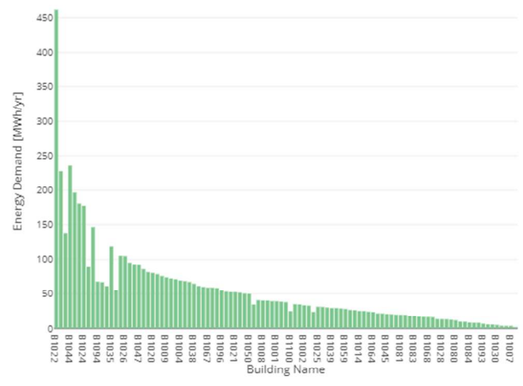
B - Space cooling demand only - BR database (MTZ1)



C - Electricity demand only - SG database (MTZ1)



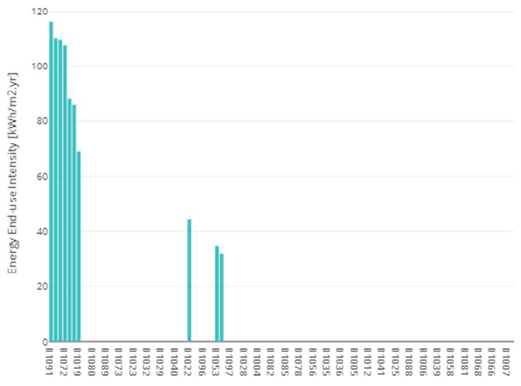
D - Electricity demand only - BR database (MTZ1)



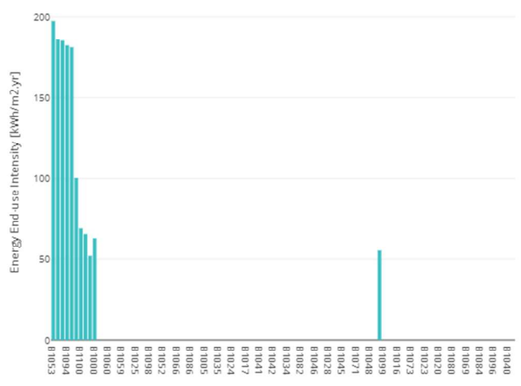
End-use space cooling demand
End-use electricity demand

Image 81: Energy end-use intensity graphs of MTZ1 (downtown Matozinhos), with both databases.

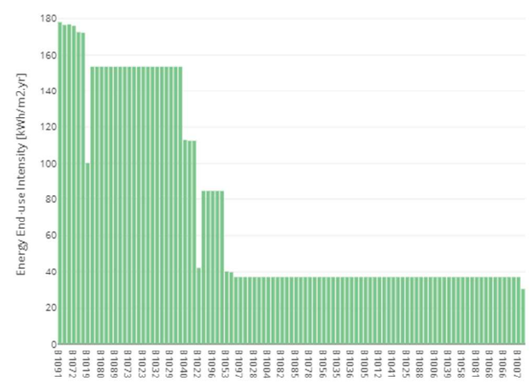
A - Space cooling demand only - SG database (MTZ1)



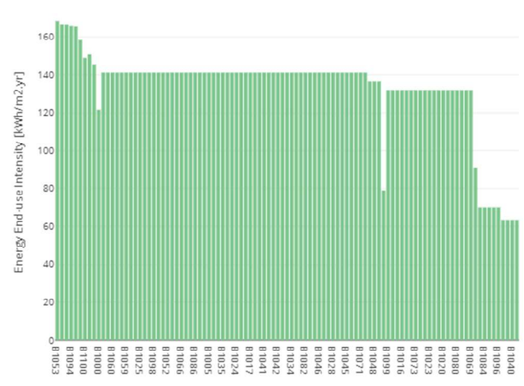
B - Space cooling demand only - BR database (MTZ1)



C - Electricity demand only - SG database (MTZ1)



D - Electricity demand only - BR database (MTZ1)



End-use space cooling demand
End-use electricity demand

Source: CEA. Compiled by the author.

In terms of space cooling demands, the energy end-use graphs generated with SG reached less than half of the maximum values displayed by the chart created with BR. An anomaly that was noticed was the absence of B1100 from the SG graph, despite it having an active HVAC system set in the Input Editor. The simulation was run one more time to check, to no avail. The BR graph displayed every one of the 11 expected buildings.

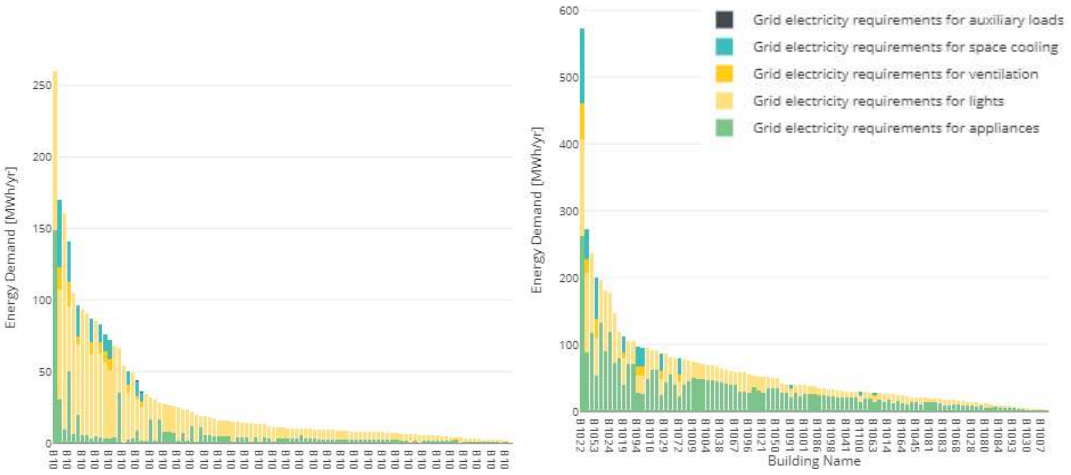
When it comes to the electricity demands, all buildings are displayed since this graph addresses appliances in general and it is possible to notice, once again, the higher values the graph generated with the Brazilian database reached. Values from building to building also showed variations when comparing SG to BR, although the majority of the less energy-demanding buildings reached relatively close numbers between SG and BR. A pattern of one building standing out among the others is seen in both SG and BR graphs.

Moving on to the energy end-use intensity graphs, more specifically those which address cooling demands only, the absence of B1100 in the SG graph is noted once again. In terms of maximum values reached, the BR graph surpasses the SG one, albeit by a shorter margin than the last.

Finally, in terms of electricity demand, the situation slightly reverses, in which the SG graph reaches a higher maximum value when compared to the BR one. In this case, however, the variation margin is even smaller than the previous electricity graph. Additionally, it is noticeable that the majority of buildings in the BR chart gets up to higher values than the majority of constructions in the SG one. Visually, both graphs followed a similar pattern in which the majority of the other buildings reached close values, forming almost a "ladder-like" pattern.

Energy Final Use and Energy Final Use Intensity

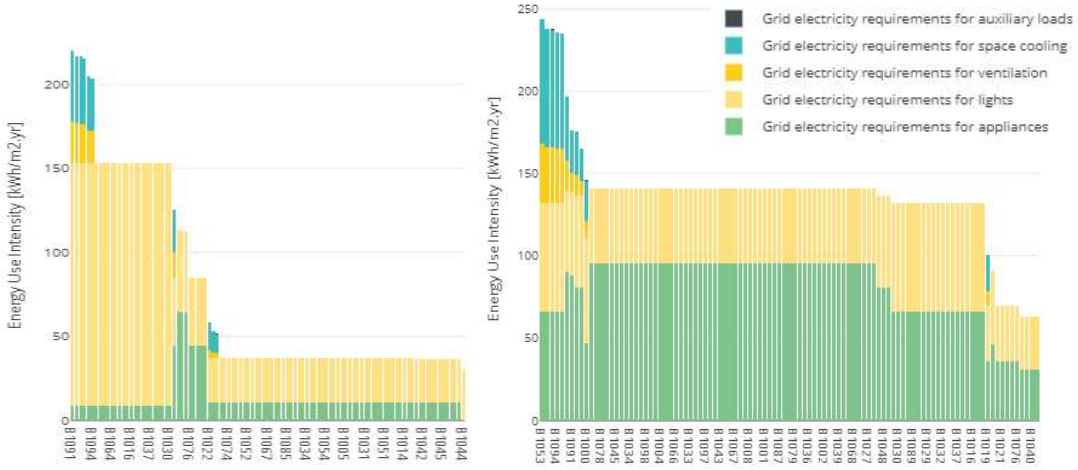
Image 82: Energy final use with SG (top) and BR (bottom)



Source: Generated by CEA.

Addressing the energy final use, it is noticeable that both graphs show a predominance of two specific uses: lighting and appliances, with the protagonism reversing in each one: while the final use graph generated with the SG database pointed to a clear predominance of the lighting over appliances, the BR database illustrated the dominance of appliances. The pattern of a single building standing out amongst the others is present in both graphs.

Image 83: Energy final use intensity with SG (top) and BR (bottom)



Source: Generated by CEA.

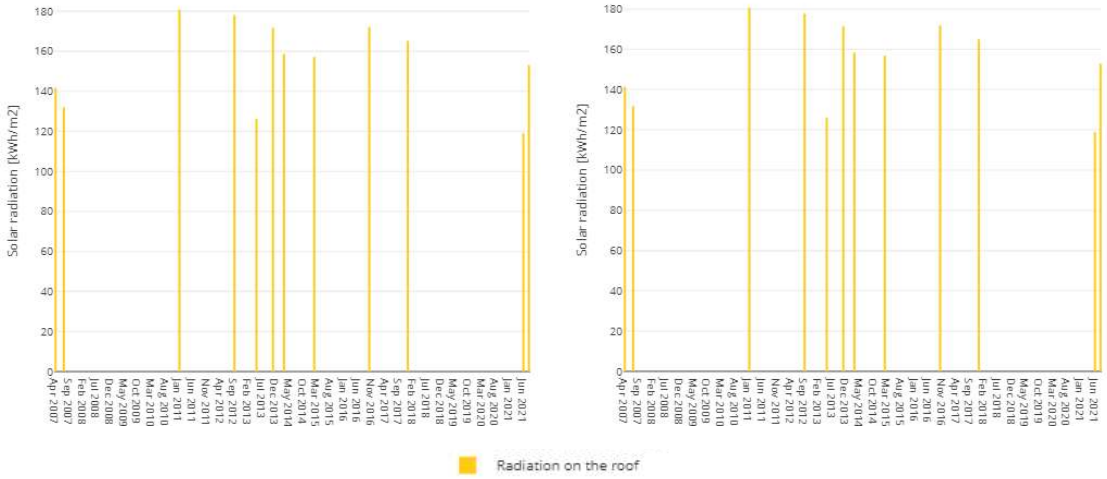
As for the final use intensity, the difference in the maximum values reached by each graph was not representative and, once again, the predominant uses were lighting

and appliances in both cases. The presence of a “ladder-like” pattern was also observed in both cases, with multiple groups of buildings reaching the same results.

Solar Potential - Solar Radiation

As expected, the graphs generated by both databases regarding the solar radiation in Matozinhos presented the same results since the weather file used was identical. In this case, the graphs presented information from all the years available in the weather file (April 2007 to August 2021).

Image 84: Solar radiation with SG (top) and BR (bottom)



Source: Generated by CEA.

In both sets of simulations, the incident solar radiation spanned from around 120 kWh/m² in June 2021 to about 180 kWh/m2 in January 2011 These months correspond to winter and summer in Brazil, respectively. Despite being part of downtown Matozinhos, the studied area does not present a considerable number of high-rise buildings as BH1 (Lourdes, Belo Horizonte) does. In fact, the majority of buildings in Matozinhos reach from 1 to 3 floors, although there are very few taller examples such as B1022 (a 6-floor MULTI_RES/RETAIL building). This fact is important to take into account when it comes to PV, PVT panels and solar collectors efficiency vs. building shading.

Technology Potentials

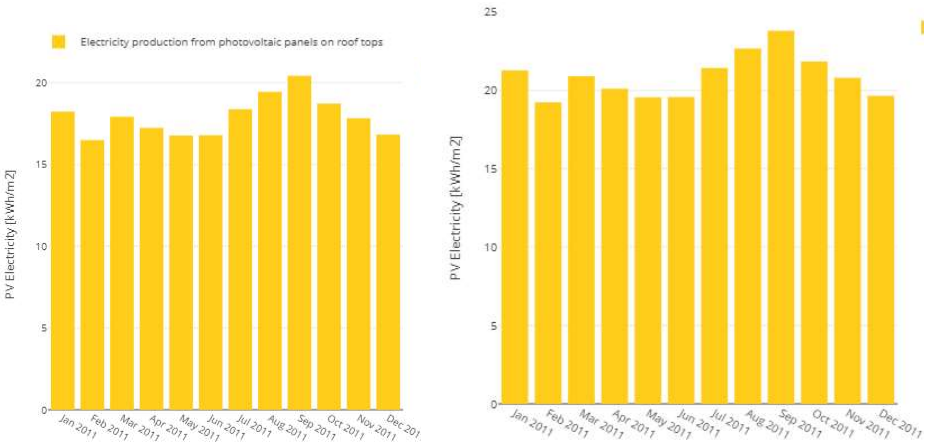
Similar to BH1 and BH2, MTZ1 also presented charts with almost identical values, regardless of the database used, due to the use of the same weather file for both of

them. Additionally, when present, the contrasts between results were not perceived as extreme in any way.

Photovoltaic (PV) Potential

In these sets of simulations, the time frame considered for both graphs was the year of 2011. Both graphs pointed to September as the month with the highest potential for electricity production. On the other hand, the month with the lowest potential for electricity production was February. With both databases, the months with the best and worst potential for production were part of the spring and summer in Brazil, respectively.

Image 85: PV electricity production with SG (top) and BR (bottom)



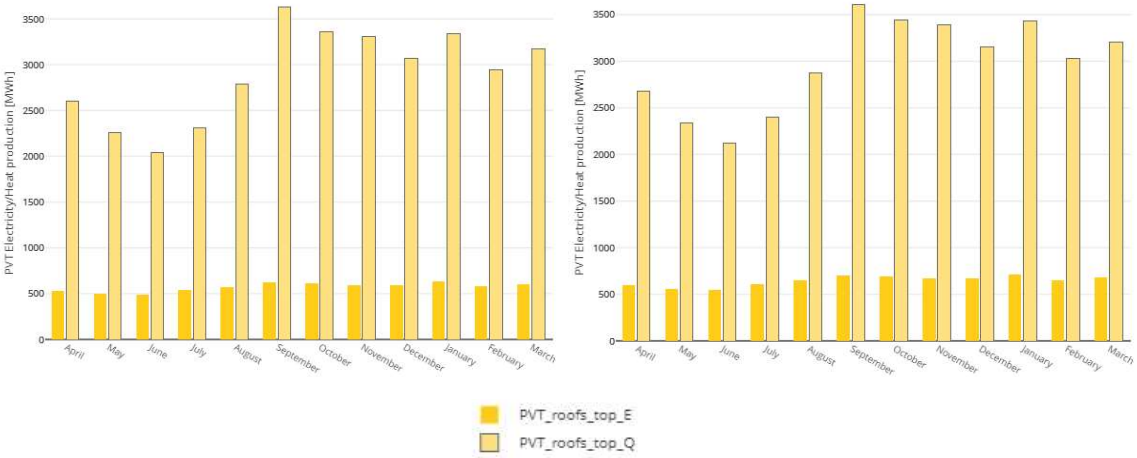
Source: Generated by CEA.

Through this analysis, it is possible to notice that the potential found are relatively similar to the ones reached in the areas BH1 and BH2, since all of the weather files are from the same city (Belo Horizonte), but in different locations.

Photovoltaic-Thermal (PVT) Potential

The following graphs regarding the electricity (PVT_roofs_top_E) and thermal energy (PVT_roofs_top_Q) production focus only on equipment installed on rooftops as well.

Image 86: PVT electricity and thermal energy production with SG (top) and BR (bottom)



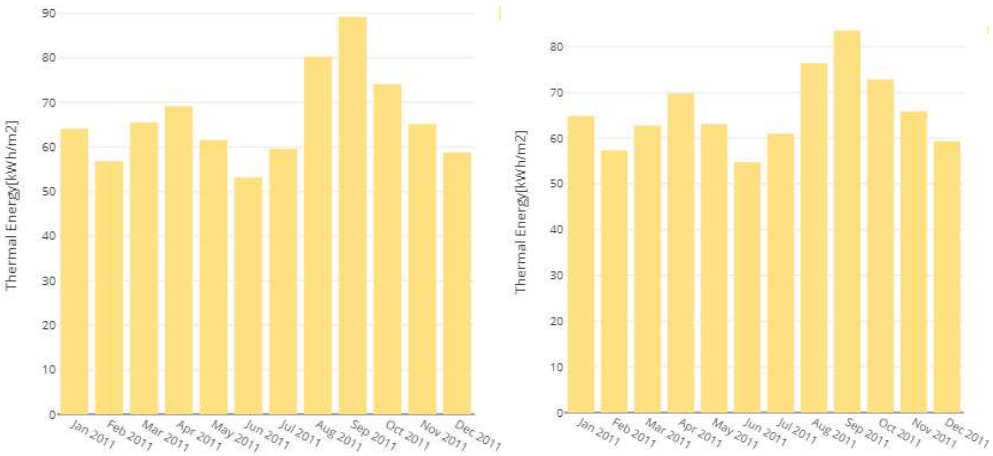
Source: Generated by CEA.

With both sets presenting similar results, the graph generated with SG pointed to September as the month with highest thermal production and January reaching the highest values in electricity. In the other extreme, June was displayed as the month with the lowest production in both thermal energy and electricity. With BR, the same months are highlighted, with slightly different results. The highest values in this area were more elevated than those in BH2, but relatively similar to BH1.

Solar Collector Potential

For the final analysis in the MTZ1 area, it is possible to notice that both graphs also displayed close results, with the SG graph (left) reaching the highest, and similar behaviors in each month throughout the simulated year, 2011.

Image 87: Heat production through solar collectors, with SG (left) and BR (right)



Source: Generated by CEA.

The graph created with the aid of the SG database illustrates September as the month with the highest thermal energy production and June as the one with the lowest. As for the BR database, its graph shows the same months presenting the highest and lowest results, with different values.

The potential found in these simulations are relatively close to the ones from the two previously studied areas due to the weather file being from the same city.

4.3.4 General considerations about the results

Concluding this section, Table 23 proposes a brief comparison of the studied areas by juxtaposing qualitative data gathered after investigating both their urban and energy contexts.

Table 23: Comparative board - BH1 x BH2 x MTZ1

ASPECTS	BH1 (Lourdes)	BH2 (Céu Azul)	MTZ1 (Downtown)
Location	Belo Horizonte, Brazil		Matozinhos, Brazil
Standards used (SG)	3 standards (1,2 3)	2 standards (1, 3)	4 standards (1, 2, 3, 4)
Standards used (BR)	6 standards (1, 3, 5, 7, 9, 11)	3 standards (1, 5, 15)	7 standards (1, 3, 5, 7, 9, 13, 15)
Building density	High	Low	Low
Examples of strengths	Data availability; robust infrastructure; economic influence.	Data availability; flexibility to implement future urban energy planning strategies	Flexibility to implement future urban energy planning strategies
Examples of weaknesses	Less flexibility to implement future planning strategies due to it being a consolidated region.	Lack of specific energy-related characterization, involving aspects such as air-conditioning in residential buildings	Lack of data in general; examples of non-compliant buildings when considering local legislations
Main similarities	Similar construction techniques; relatively similar climate; close scenarios when it comes to electricity distribution.		
Main differences	High-rise buildings with multiple uses are common; part of the “formal city”; an economically thriving region.	Low-rise buildings; examples of “atypical settlements” are found in its territory; predominantly residential.	Mainly low-rise buildings with few exceptions; a small town; examples of “atypical settlements” are found.

Source: Created by the author.

In general, the simulations presented results somewhat promising in terms of having a more local database available, meaning that it would be likely easier to gather

results that are closer to the local reality. Furthermore, some data tracks with the local reality, such as the predominance in appliances, lighting and cooling systems in the energy demand of some buildings or the solar radiation study. It is believed that, if there was a possibility to add more details to the appliances part in the schedules, such as the use of electric showers, the energy demand results could be even more precise and its impacts could be further studied.

There were also some results with expected limitations. In scenarios where HVAC systems would be either split or window types, there was no detected variability in the energy demand of each type and the reason for that lies on the fact that, in the BR database, there was no clear differentiation between each equipment due to the lack of the necessary information in the examined regulations. In the chance of the BR database being updated, it is recommended that the process is done by a multidisciplinary team, including a specialist in HVAC systems. This way, eventual gaps might be solved and the database might be further expanded to eventually cover Brazil in its entirety, as it is intended to be.

Despite the promising results, some unexpected outcomes that need to be studied in depth were also noticed:

- Considerable differences were spotted in the comfort charts, despite the weather file being the same in both sets of simulations;
- The presence of both occupied and unoccupied hours in some graphs and the absence of the latter in others;
- In some buildings, the “sensible heat loss through ventilation and infiltration” reaching higher values with SG than with BR was not expected due to the fact that, in Brazil, window tightness standards are not even close to be as restrictive as they usually are in other countries;
- There were visible discrepancies in the graphs ranges between databases when it comes to energy use, intensity and final use;
- The software did not present enough sensibility to atypical settlements, with graphs not even being generated.

With that being said, there are some functionalities in the software that are ready to be immediately used in Brazil:

- “Building Solar Radiation”: Crucial variable to study available solar radiation in the area and, consequently, the energy potentials linked to solar energy. It is also relevant to analyze the need for shading devices in certain buildings taking the influence of its surroundings into account;
- “Energy Potentials” (more specifically, PV, PVT and solar collectors): Relevant data to investigate the applicability and possible performance of technologies to produce on-site electricity and, when applicable, thermal energy.

Other analysis options such as “Optimization” and “Networks” were not intended to be addressed in the present research. Therefore, they are not going to be ranked in this regard.

It is relevant to mention that the Brazilian database created was submitted to the CEA developer team at ETH Zürich in order to have it validated and possibly included in future CEA versions. Additionally, it was also submitted to CTIT-UFMG (*Coordenadoria de Transferência e Inovação Tecnológica,* or Coordination for Technological Transfer and Innovation, in Portuguese) to be registered.

5. ADDITIONAL RESEARCH DEVELOPMENTS

This chapter is destined to highlight three developments that originated from the present research, one of them set as part of its objectives and the other two as an additional development that helped link two of the three areas worked in a university: research and teaching. The first one is an educational video that aims to bring this work topic closer to public policy makers and urban planners; the second, an undergraduate module offered at UFMG from March to May, 2024; and the last one, a short course given during a national conference called ENSUS 2024.

5.1 Educational video

The video created at the end of this research was targeted at policy makers and urban planners in general, in order to help bring the topic of Urban Energy Planning closer to those who make decisions that can impact a city. The video, in summary, was divided into the following moments:

1. Presenting the researcher and the research topic;
2. The reason why this topic is relevant for cities;
3. How the main actors involved in the process can act;
4. Final considerations.

The video can be accessed on Youtube through the QR Code displayed below.

Image 88: QR code that grants access to the educational video.

Source: Created by the author.

5.2 Undergraduate module at UFMG

Called "*Simulação Computacional Aplicada ao Planejamento Energético Urbano*" (Computer Simulation Applied to Urban Energy Planning, in free translation), the module was offered in the first semester of 2024 at UFMG School of Architecture and had 24 students enrolled. The main objectives were to introduce them to the topic of computer simulations in an urban scale and to apply the BR database in a practical way for the first time, investigating its performance.

5.2.1 Module origin and brief scope

The mentioned module originated directly from the present research and was offered for the first time from March to May 2024. It was composed of a mix of both theoretical and practical classes, as Table 24 illustrates, that introduced the students to the topics already addressed in this work: computer simulations, Urban Energy Planning and the CEA software.

Table 24: Module structure

Date	Duration	Language	Topics
March, 15th	From 2 p.m. to 5:20 p.m. (local time)	Brazilian Portuguese	- Module introduction and groups setting; - Energy-related theoretical concepts
March, 22nd			- City Energy Analyst - An introduction; - Practical moment with test simulations.
Apr. 5th			- CEA original database: contextualization and relevance
April, 12th			- Modeling on OpenStreetMap: a theoretical introduction; - Practical modeling moment.
April, 19th			- Introduction of the first BR database for CEA; - Practical tests with said database.
Apr. 26th			- Class focused on simulations, tests and student support.
May, 3rd			- Student support for results collection and presentation.
May, 10th		English	- Final seminar. Guests: Dr. Zhongming Shi (ETH Zürich, through video call), Dr. Camila Ferreira (UFMG, in person) and Dr. Raquel Diniz (CEFET-MG, in person).

Source: Created by the author.

As it is possible to notice in the previous table, apart from the first lecture, all the others had both theoretical and practical moments in order to link the recently learned information to a hands-on approach. In terms of the language used, the

majority of classes were lectured in Portuguese with one of them being in English due to the presence of an external guest representing ETH Zürich.

One difference this module had compared to the present research is the number of studied areas, with the former being based on four urban regions (see Image 89). The reason for the reduction is the remaining time frame available for the research and the fact that CEA did not present enough sensibility to study atypical settlements, the main reason why the fourth area was added to the module in the first place.

Image 89: Studied areas defined for the undergraduate module

Source: *OpenStreetMap*. Created by the author.

The additional area was part of a residential neighborhood in Matozinhos called *Bom Jesus*, with its choice defined by the same logic as the one applied to *Céu Azul*, in Belo Horizonte. The climate data used is addressed in the next topic. As for the input definition regarding the buildings characterization, the process was done by each group individually using Google Street View and the BHMap website when needed.

5.2.2 Module methodology

Being created and offered by the author of the present research and her supervisor, the 30-hour module was divided into 8 classes and was targeted at undergraduate students. Seven of the eight classes were ministered in a computer lab at the university, except for the introductory lesson, and extra-class communication was done through the Microsoft Teams platform. Additional class material was also made available using the same platform.

With the exception of the inaugural class, the others had both theoretical and practical moments, with the latter being the predominant form of teaching and taking up most of the class available time frame. The classroom of 24 people was divided into four groups of 5 to 7 members, in order to study each of the four available urban areas (sections of *Lourdes* and *Céu Azul*, in Belo Horizonte, as well as downtown

Matozinhos and *Bom Jesus*). The more complex the area was and the less available data it had, the bigger the group studying it would be. The choice for these urban areas follows the same logic as the one used in the present work.

Also similar to the present research, the module focused on CEA version 3.34.2 due to several incompatibilities that appeared between the latest versions of the software and the computers in the university lab. The three areas that were not previously available on CEA (Céu Azul, downtown Matozinhos and Bom Jesus) were modeled by the students through the OpenStreetMap platform. The former two were used in the present research.

As input, two forms of data were used during the module: the weather files and CEA databases. For the former, the following files were used:

- BH1 (Lourdes / Belo Horizonte): Belo Horizonte-Carlos Prates;
- BH2 (Céu Azul / Belo Horizonte): Belo Horizonte-Pampulha;
- MTZ1 (Downtown Matozinhos): Belo Horizonte-Confins;
- MTZ2 (Bom Jesus/Matozinhos): Belo Horizonte-Confins.

As for the CEA databases, both BR and SG were used in all areas. Each group investigated their urban regions and used said databases to characterize their buildings and surroundings accordingly. The aim was to allow, after the simulations were run, a comparison between databases. Table 25 illustrates the scripts that were run in each area by the groups for the final seminar.

Table 25: Scripts run in each urban area

Tabs	Scripts	Purpose of the scripts
Data Management	Archetypes mapper	Defines properties for buildings and systems.
	Weather helper	Defines the weather file to be used.
	Surroundings helper	Extracts 3D shapes from OpenStreetMap.
	Terrain helper	Defines topography with a specific elevation value.
	Streets helper	Extracts roads from OpenStreetMap.
Demand Forecasting	Building solar radiation	Calculates solar radiation of a scenario.
	Building schedules	Defines occupation schedules.
	Building energy demand	Calculates building energy demand.
	Photovoltaic-thermal	Calculates electricity and thermal energy production

Energy potentials	panels	from hybrid panels.
	Photovoltaic panels	Calculates electricity production from PVs.
	Solar collectors	Calculates thermal energy production from solar panels.
	Shallow geothermal potential	Despite not being representative in the studied regions, since it involves thermal energy from these sources, they were included in order to draw a comparison between the results with the SG and BR databases.
	Water body potential	
	Sewage heat potential	

Source: Created by the author.

Similar to the present research, the undergraduate module did not perform any simulations regarding emissions due to the reasons already stated. The final seminar was presented fully in English. Each of the groups presented their results and had comments and questions directed at them.

This undergraduate module aimed at guiding the students in the path of forming their own critical thinking regarding simulations in an urban energy planning scenario, as well as discussing the results gathered from the simulations using both databases and analyzing the software complexity.

5.2.3 Discussions

In the inaugural class, it was noted that there was a mix of students who have had previous contact with simulations before and those who have not, with most of the participants being unfamiliar with the use of computer simulations as planning tools. It was also during the first class that it was proposed for the students the possibility of the final seminar to be conducted in English while having an external guest from abroad. All the groups were formed later on with at least one member in each being fluent or, at least, comfortable at speaking English.

The next class started with an objective theoretical contextualization followed by practical exercises. The first simulations run with the students had a similar goal as the test simulations of the present research: not to collect and analyze data, but to understand the software and its tools. For this, a small section in downtown Belo Horizonte was used as a case study. After the trial simulations, it was noticed that despite CEA having a clear user-friendly interface when compared to other similar softwares, the simulation process still was not completely intuitive for everyone as

expected. Naturally, the individual experience level that each student had prior to that moment also interfered in this outcome.

One of the first obstacles faced was the impossibility to run more robust simulations with the brand-new computers at the university lab with the, at the time, latest CEA version (3.35.5). The system would crash whenever the solar radiation simulations were performed and the computers would turn off unexpectedly. Additionally, there were several reports from students that had the same outcome when installing that version on their personal laptops. For that reason, the 3.34.2 version was adopted for the remaining time of the module, since it did not present the mentioned issues. These obstacles were then reported to members of the CEA team at ETH Zürich, who were considerably helpful and cooperative through the whole process.

During the practical moments, one of the most frequent doubts from the students was in regards to input configuration, something that is absolutely crucial to the success of any simulation. It was also pointed out to students how important it was for them to refine their critical thinking to be able to see which variables would be more or less relevant in a Brazilian scenario and the reason behind it. During the same practical moments, doubts regarding the software and eventual bugs were also solved and, when necessary, reported back to the development team. The practical use of OpenStreetMap, during class 4, did not present any obstacles and the students reported being comfortable in using it.

While formally dealing with the studied areas, the participants were presented with the two main databases for the simulations: the original SG database and the recently created BR one. Parallels between the Singaporean and Brazilian realities were drawn while also presenting each collection of data simultaneously, pointing some similarities and differences between them when it came to the information they contained. Practical tests were performed and new errors were detected, being solved by the students after the author and her supervisor offered them technical support sessions. It was noticed that, by that point, there were still some lingering doubts regarding the input configuration phase, which led up to an extra tutoring moment to help the students. Some errors took longer to be solved than expected, which left the remaining time to perform simulations slightly unbalanced.

The last class before the final seminar was mostly dedicated to conclude the simulations and prepare to gather the results. A variance among the groups in terms of development was noted, with some being close to finishing their simulations while

others were still struggling with improving their input configuration process. This divergence lasted until the end of the class. After every presentation during the final seminar, the ETH Zürich representative presented his comments, questions and compliments to the students. The other two guests took part as listeners, presenting their comments in the last moment of the class when a more informal discussion session was carried out and the module and software relevance in a Brazilian context were debated.

5.2.4 Main considerations

In terms of results gathered by the students, it was noticed that some got similar outcomes regardless of the database used, which was unexpected, while others did get different numbers between databases. It was also noted that some variables did not show up in the graphs, such as hot water consumption, which was also an anomaly. Preliminarily speaking, it is possible to justify these atypical situations with two hypotheses: the first being a low level of sensibility the software had with the differences between the Singaporean and Brazilian urban and energy realities; and the second being a possible error during the input configuration phase.

Some observations were made by the author and her supervisor throughout the classes, as well as during the final seminar:

- The initial errors originated from the latest version of the software and other bugs detected during the simulations consumed a considerable portion of the time. This fact, combined with the unfamiliarity of a portion of the student body with computer simulations, led up to the fact that the final results were only gathered by the end of the last class. Nonetheless, the flawless dedication presented by the students was noticed during this whole process. It is possible to conclude that the learning process was promising;
- It was noticed that some students appreciated the combination of a theoretical approach with the predominance of the practical moments, as well as the support given by the author and her supervisor;
- Problems with the university Wi-Fi connection were reported by the students, which affected some moments in class that culminated in part of the practical work to be done at home;
- Problems during the installation process of CEA and several setbacks in its use were also reported, as previously mentioned;

- Due to the differences noticed in the final classes regarding the development journey of the students and the doubts linked to input configuration mentioned by them, a restructuring of the course syllabus might be necessary in order to improve the proportion of theoretical and practical moments and ensure they fully cover the most vulnerable spots reported by the student body. This could also include additional exercises addressing topics such as urban interventions made possible after an analysis using CEA and an intermediate work submission of preliminary results generated by the students.

In terms of suggestions for the software, the following topics were pointed out:

- The possibility to include in its variables some aspects that could consider the link between building uses and the economic potential of each area;
- Improvement of the legends of the graphs, switching the acronyms and abbreviations to full words to facilitate the results interpretation;
- Allow the graphs to be displayed in a clear and more direct way, with no bars overlay. Instead, those same bars could be displayed side by side whenever the same graph would show more than one variable at the same time.

In general, the students came up with compelling analysis and some expressed interest for the module to be longer to allow deeper studies. They concluded it with a more mature critical thinking process when it came to applying simulations in an urban energy planning scenario. The studied areas were successfully contextualized by the participants when presented to a person from outside of Brazil, which is considerably important to highlight. Overall, the undergraduate students were able to answer most of the questions directed at them and they considered the English-guided seminar to be a relevant new experience.

The fact that the undergraduate students had a promising performance and that their critical thinking visibly matured during this robust syllabus compiled in only 8 classes motivated the author and her supervisor to offer this module again in the following semester. Another positive point was having an external guest as part of the final seminar, further strengthening the partnership between UFMG and ETH Zürich.

When it comes to the applicability of CEA, it was noticed that some difficulties previously mentioned by the students started to be naturally overcome due to the software user-friendly interface. On the other hand, some errors consumed a considerable amount of time to be solved. However, it is relevant to point out that

such situations are relatively common when dealing with computer simulation tools, which was emphasized to the students as part of the learning process.

Generally speaking, regardless of the obstacles faced throughout this experience, the module was successful in achieving its goals. Empowering students while they are still at university is a key fact to enhance the relevance and awareness of future architects who will one day create work that impacts the urban scale.

5.3 CEA introductory course at ENSUS 2024

On August 9th, a 2-hour course about CEA was given by the author at ENSUS 2024, a conference dedicated to discuss sustainability in projects that took place in Belo Horizonte this year, organized by UFMG. In this course, the software, its purposes and functionalities were presented through a theoretical point of view, followed by a practical exercise in which the lecturer guided the participants through the process of setting the variables to be simulated. This course was also kindly promoted by the CEA team on their website. In total, 6 people attended and the CEA versions used by them were 3.37.x and the Web version.

Image 90: Theoretical part of the course

Source: ENSUS 2024 team.

Due to the limited time available for the course and the need to build a short theoretical basis with the participants beforehand, the practical moment was not long enough to perform every simulation CEA has to offer. However, since the author had the simulations already run, it was possible to guide the participants through the input configuration process and the results visualization.

It was noticed that the topic of Urban Energy Planning and CEA itself were not known among the participants. Even though some had difficulties in using the software for the first time, they expressed enthusiasm throughout the course, understanding the potential of the topic and the software while asking relevant questions along the way.

6. CONCLUSIONS

This research focused on analyzing the suitability of City Energy Analyst (CEA) in Brazilian scenarios, identifying possibilities or adaptations for it and its database to bring them closer to the local reality. It also originated the first version of a Brazilian database for CEA, intended to be applicable to Belo Horizonte and Matozinhos, as well as any other Brazilian city that presents similar urban and energy contexts. Said database is available in two versions (CEA 3.34.2 and 3.37.x). As additional developments, this work produced not only an educational video targeted mainly at policy makers and urban planners, but also originated an undergraduate module offered at UFMG that brought direct contributions to this work and a short course that took place in a scientific event in Belo Horizonte.

The theoretical basis permeated through key areas to the central topic addressed. The contextualization of the studied regions complemented these chapters by giving a local point of view and introducing some aspects that would be relevant during the formal simulations, such as the urban fabric of both cities, access to electricity and basic characteristics of their microclimates. This knowledge framework supported the definition of data to be inserted into the new Brazilian database.

Regarding the simulations, the results between databases were considerably different in terms of values, which was somehow expected due to the vast peculiarities of each database, such as its technical data and occupancy patterns. Qualitative speaking, there were some similarities such as the predominance of appliances and lighting systems in the energy demand of some building types. As expected, the uses, construction characteristics and occupation patterns impacted their respective results. Through these simulations, it was possible to draw some major conclusions in regards to CEA and the Brazilian context:

- Strengths: CEA presents a considerably interesting potential to be used in Brazil, not only for its relevant variables analyzed, but also for its user-friendly interface that brings the software closer to the user and allows them to dedicate more of the simulation time to crucial moments, such as input configuration and results analysis;
- Limits: Some major aspects that are of utmost importance in local realities were unable to be included into the new database due to the current inability of the software to analyze this type of data. Thermal energy sources used for

cooking purposes are also a considerable part of Brazilian scenarios, but could not be added due to the same situation. Additionally, CEA did not present enough sensibility to interpret scenarios where atypical settlements were involved. They are examples of buildings that would contain more affordable energy and cooling solutions. Enabling such appliances, energy sources and urban characterizations could bring CEA even closer to not only Brazilian scenarios, but also other countries with similar backgrounds.

Through the simulations of the three studied areas and analysis of their results, some suggestions were thought in order to not only bring the software even closer to Brazilian scenarios, but also facilitate the user experience even further:

- Provide a way to include variables that accept the items mentioned previously (electric showers, LPG for cooking and floor fans for cooling). This could partially help describe the Brazilian energy matrix in a more detailed way;
- Make graph legends/captions more straightforward, with full words instead of abbreviations;
- Make the bars graphs without overlapping data in order to make the analysis process more direct;
- Provide the possibility of visualizing some results on the software 3D view, such as the radiation levels on roofs and walls. The color scheme could follow a similar logic to other platforms, such as Google Solar. This, combined with the shading the surrounding buildings would create, could generate relevant information linked to, for instance, the impact of urban verticalization in the performance of PV panels, PVT panels and solar collectors. This data is useful not only for the consumer who wants to install such equipment, but also to local authorities who want to evaluate these forms of impacts in order to improve local legislations, for example;
- Provide more variables linked to natural ventilation, since it is one of the most relevant passive strategies in Brazil that also impacts positively on the energy demand for cooling. As examples of variables that can interfere in this topic, it is mentioned the ventilation opening factor (*fator de abertura*, in Portuguese) for each type of window presented by the databases and surface roughness;
- Allow the user to insert more details about the interior of the building, such as thermal zones and the percentage of ambients with and without any cooling systems in place - after all, not necessarily an entire building might be

artificially conditioned. This type of data would impact topics such as the energy demand, so a more detailed characterization could be beneficial;

- On CEA, when some settings are altered (e.g.: the weather file of one specific scenario), there is only the possibility to save such change as a default for all the other scenarios and simulations (“save to config”), which forces the user to alter said definition constantly. As a generic example, if the user sets for a scenario the file “Belo Horizonte-Carlos Prates” as the weather file and saves it, it will appear as the default option in a second different scenario. If it is not the correct file for the latter, the user will need to change it again and set it to another file (“Belo Horizonte-Pampulha”, for example). When back to the first scenario, the weather file set would be the last one changed by the user, meaning “Belo Horizonte-Pampulha”, and not “Belo Horizonte-Carlos Prates”. This forces the user to constantly check said variable to ensure it is the correct one, which can be time consuming. It could be interesting to have an additional form of saving the configuration for that scenario alone, without interfering on the other ones that are present in the same project folder;
- When saving images of the results generated by the software, those examples with such a long list of variables in its legend that a scrollbar is present, such as energy balance graphs, tend to not be fully displayed in the PNG image. It could be interesting to offer a possibility to save the full image right away.

As previously mentioned, there were some findings that require further analysis to deeply understand the reasons behind them:

- Investigate the reason for the considerable differences that were spotted in the comfort charts, despite the weather file being the same in both SG and BR simulations of each area;
- Understand the reason behind the presence of both occupied and unoccupied hours in some comfort charts and the absence of the latter in others;
- Study why the “sensible heat loss through ventilation and infiltration” variable reached higher values with SG than with BR in some buildings;
- Explore in detail the visible deviations in the graphs ranges between databases when it came to energy use, intensity and final use;
- Look into the reasons why CEA did not present enough sensibility to atypical settlements, with graphs not even being generated.

Solving the unit conversion limitation regarding emissions in BR is one of the main possibilities for future research, as well as doing the same in order to add more energy options in the Feedstocks table, such as LPG as a thermal source for cooking. Additionally, the upgrade when it comes to the HVAC systems definitions and the information within the “Distribution” table are also potential topics for future works due to the lack of some data in local regulations or the adoption of values from SG. It is also suggested an additional and individual evaluation of absolute values in each simulation in order to measure the size of the impact that mixing local information with data from SG could have had on the results. An expansion of typology uses in the “Use_Types” folder is also encouraged since the options included in BR were the ones currently available in Brazilian regulations. Last but not least, it could be relevant to conduct a benchmark study comparing the results in the energy demand graphs calculated by CEA in the studied areas with real values from the same simulated buildings.

This research intended to contribute not only to the discussion regarding the addressed topics, such as computer simulations applied to Urban Energy Planning, but it also sought to be relevant in the debate of including in large-scale softwares examples of social and urban realities that may not be common to developed nations, but are part of the construct of several emerging countries. Through the theoretical foundation, it was stated how these tools can be fundamentally important in decision-making processes and how said decisions, when in an urban scale and dealing with local regulations, can impact several people. Therefore, allowing said tools to interpret a multitude of urban and energy realities would be beneficial on a collective scale. Additionally, in order to have a comprehensive debate on relevant topics nowadays, such as urban planning, decarbonization and energy transitioning, it is crucial to include both financially gifted nations and emerging countries.

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