Energy Management – TekiniKicukiro

Final Report

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Executive Summary

The project presented in this report studies the possibility of implementing an energy transition plan for the district of Kicukiro. The study is based on three distinct scenarios: Business as Usual, Circular Economy and Renewable Energy Community, each exploring ways towards sustainability in the sectors of public transport, cooking, buildings, and electricity generation.

An analysis of Kicukiro's current energy mix was made, revealing high electrification rates, reliance on biomass for cooking, and increasing interest in electric vehicles (EVs), especially for public transport. Based on this, each scenario was modelled using several tools: IDA ICE, ArcGIS Pro, and HOMER Pro to assess technical feasibility, energy demand, and economic performance.

The Business as Usual scenario reflects projected development under existing policies. The Circular Economy scenario integrates biogas technologies, from local organic waste streams, enhancing sustainability, particularly for public transportation. The Renewable Energy Community scenario exploits solar photovoltaic systems, mainly rooftop PVs, a ground-mounted solar park in the partially decommissioned airport and energy storage to enable energy self-sufficiency and citizen participation.

Key Performance Indicators (KPIs) were established to assess total energy demand, renewable share, self-sufficiency, clean cooking adoption and green transport integration. These are used to perform a comparison between the different scenarios, to understand their strengths and vulnerabilities.

The economic assessment, including Net Present Value (NPV), Internal Rate of Return (IRR), Benefit to Cost ratio (BTC), Discounted Payback Period (T_{dp}) and sensitivity analyses, enhances the financial viability of community-owned renewable energy solutions. The business model, LUMA (Local Utility Membership for All), aims to focus on citizens and promote equitable access to clean energy.

Overall, the study highlights Kicukiro's potential to serve as a model for sustainable urban development. By embracing circularity and local renewable generation, the district can ensure long-term energy security and reduce environmental impact.

Chapter 1

Personal Contribution

1.1 Andrea Gaetani

1.1.1 Contribution to the project

- Contribution to the literature review (current situation regarding electricity, buses, climate in Rwanda).
- Contribution to the creation of scenarios.
- Fully responsible for the quantitative modelling with HOMER Pro (system's layout, technologies costs, scenario implementation, transports' loads).
- Fully responsible for the post-processing of the HOMER Pro results and Pareto charts creation.
- Contribution to the sensitivity analysis (HOMER Pro simulations and charts creation).
- Contribution to the evaluation of projections regarding the public transport sector.
- Contribution to the cooking sector calculations.
- Contribution to the KPI analysis and results quantification.

1.1.2 Contribution to the report

- Contribution to the writing of Chapter 2 (2.1).
- Contribution to the writing of Chapter 3 (3.1).
- Contribution to the writing of Chapter 4 (4.2.1).
- Contribution to the writing of Chapter 5 (fully responsible for Section 5.6 - HOMER Pro and its corresponding Appendix).
- Contribution to the writing of Chapter 6 (6.1.1, 6.1.4).
- Contribution to the creation of graphs and tables.

1.2 Marta Ruggerini

1.2.1 Contribution to the project

- Contribution to the literature review (current situation regarding built environment, buses, housing and clean cooking in Rwanda and Kicukiro district).
- Contribution to the creation of scenarios.
- Contribution to the creation of the System Mapping.
- Contribution to the quantitative modelling with IDA ICE.
- Contribution to the evaluation of projections regarding Buildings and Cooking sectors.
- Contribution to the KPI analysis and results quantification.
- Conception of the Business Model Innovation.

1.2.2 Contribution to the report

- Contribution to Executive Summary.
- Re-arrangement of the Introduction.
- Contribution to Chapter 3. (Fully responsible of Section 3.4).
- Contribution to Chapter 4. (Fully responsible of section 4.1, 4.4).
- Contribution to Chapter 5. (Fully responsible of section 5.1, 5.3).
- Creation of the respective sections in the Appendix.

1.3 Mariolina Stålhös

1.3.1 Contribution to the project

- Contribution to the literature review (current situation regarding the energy and electricity, transportation and state-of-the art information about Rwanda and Kicukiro).
- Contribution to calculations in the transport sector (load of EV:s and predictions for buses).
- Contribution of data gathering for costs and the calculations of all the OPEX values).
- Contribution to the cost analysis.
- Contribution to the Business model idea.
- Contribution to the sensitivity analysis.

1.3.2 Contribution to the report

- Contribution to Chapter 2 (for 2.1, 2.3 and fully responsible for 2.2)
- Contribution to Chapter 3 (3.1 and 3.3).
- Contribution to Chapter 7 (7.2, and fully responsible for the writing of the Pareto frontiers in 7.1).
- Fully responsible for Appendix 10.6.
- Fully responsible for the writing in Chapter 8 (Business model).

1.4 Alejandro Fernández Tomé

1.4.1 Contribution to the project

- Contribution to the literature review (current situation regarding built environment, housing and clean cooking in Rwanda and Kicukiro district)
- Contribution to the creation of scenarios.
- Contribution to the creation of the System Mapping.
- Fully responsible for the quantitative modelling with ArcGIS Pro (building archetypes distribution and geometry parameters).
- Contribution to the quantitative modelling with IDA ICE.
- Contribution to the evaluation of projections regarding Buildings and Cooking sectors.
- Contribution to the KPI analysis and results quantification.
- Contribution to the conception of the Business Model Innovation.

1.4.2 Contribution to the report

- Contribution to Executive Summary.
- Contribution to the writing of Chapter 3 (fully responsible for Section 3.2).
- Contribution to the writing of Chapter 4 (Section 4.3).
- Contribution to the writing of Chapter 5 (fully responsible for Sections 5.4 and 5.5 - ArcGIS Pro and IDA ICE and their corresponding Appendices).
- Contribution to the creation of graphs and tables.

1.5 Alexandra Bermudes Machado

1.5.1 Contribution to the project

- Contribution to the literature review (current situation in the transport sector)
- Responsible for the public transport sector calculations (load of biogas buses and diesel buses; conversions, and shares). Contribution in projections for all scenarios in this sector
- Contribution to cost analysis (gathered information for investment costs in the public transport sector)
- Contribution to the sensitivity analysis (Excel treatment and chart creation)
- Contribution to the visual design of the Business Model Innovation

1.5.2 Contribution to the report

- Creation of report layout
- Responsible for Executive Summary
- Contribution to Chapter 3 (partially section 3.3)
- Contribution to Chapter 5 (Fully responsible for Section 5.2)
- Contribution to Chapter 6 (Subsubsection 6.1.3)
- Contribution to Chapter 7 (Fully responsible for Subsection 7.3)
- Contribution to Conclusions
- Fully responsible for Appendix 10.2

1.6 Antoine Démoulin

1.6.1 Contribution to the project

- Contribution to the literature review (current situation regarding electricity in Rwanda, water treatment and infrastructure, state of the art of the Waste management in Kigali).
- Contribution to the initial idea of a Water and hygiene (Wash and sanitation) based KPI (discontinued).
- Contribution to the calculations regarding the feasibility and dimensioning of the biogas digesters (broad literature review and data collection, set up of the excel spreadsheet).
- Contribution to the Business model realization (mostly finding a realistic and feasible way of realizing the idea, finalizing the details making it possible. Jointly worked out the Business Model Canvas with Mariolina).
- Contribution to the economical analysis (finding realistic and senseful ways to quantify and compare the benefits and costs associated to each scenario, and especially the different technologies used. Fully in charge of setting up the formulas and calculating all the indicators used for the comparison of the scenarios).

1.6.2 Contribution to the report

- Setup of the Overleaf (LaTeX) environment.
- Contribution to the writing of Chapter 7.
- Contribution to the creation of tables.

Chapter 2

Introduction

2.1 Rwanda

Rwanda is located in central Africa, bordering with Uganda, Tanzania Burundi and Democratic Republic of Congo. It is the most densely populated country in Africa, with a population density estimated at 445 people per km². It is well known for its hilly, fertile landscapes that have attracted an increasing number of tourists in the last years [1]. The climate is characterized by four seasons, two dry and two wet, with an annual average temperature of 22°C. Heavy rainfalls are present during the wet seasons. In Rwanda, solar energy has a potential of 4.5 kWh per m^2 per day and approximately 5 peak sun hours, creating an ideal location for solar PVs [2].

In the charts below, the annual variation of Rwanda's solar DNI (Direct Normal Irradiance), temperature and wind speed is presented. It can be seen how both the temperature and the DNI have a low fluctuation all year round, with values that are well-suited for solar energy purposes. The wind speed, with an average of 3.16 m/s, suggests low potential for the installation of wind turbines.

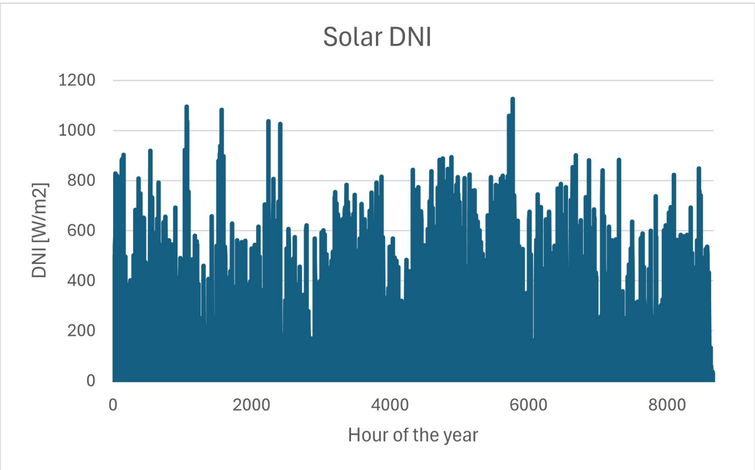


Figure 2.1: Rwanda (Kigali) solar DNI potential during 2023 [3]

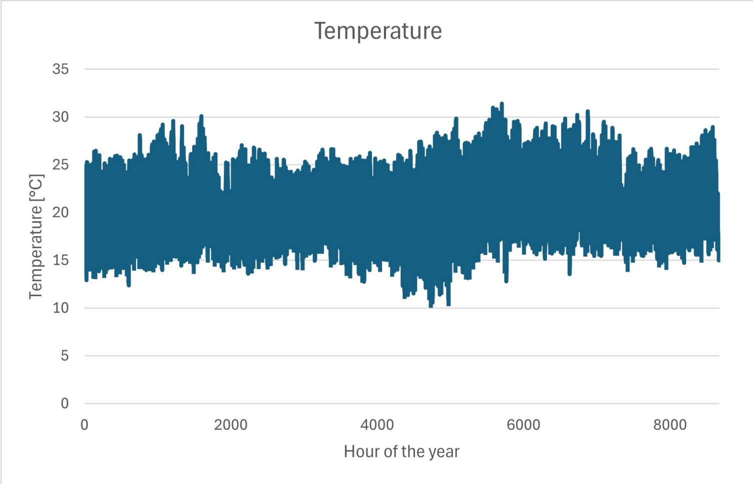


Figure 2.2: Rwanda (Kigali) temperature during 2023 [3]

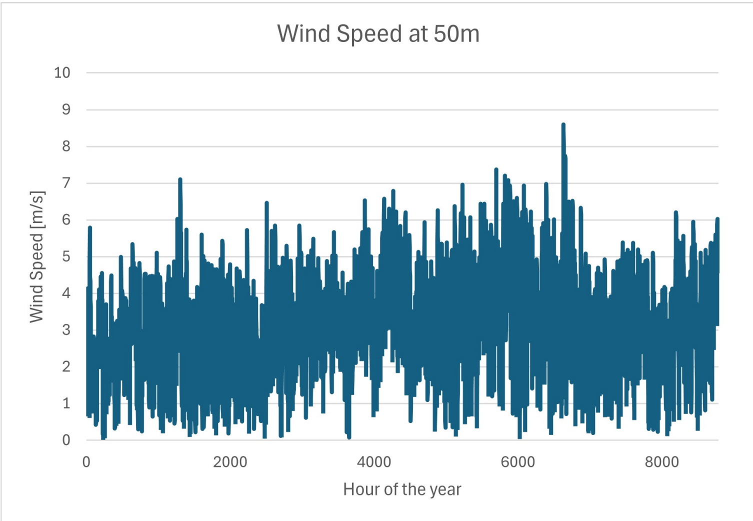


Figure 2.3: Rwanda (Kigali) wind speed during 2023 [3]

2.2 Kigali

Kigali is the capital of Rwanda and it is divided in three districts: Gasabo, Nyarugenge and Kicukiro. It has an annual urbanization rate of 4% [4]. The demand for clean energy grows as the infrastructure develops. This pressures the city's energy infrastructure, therefore it is necessary to find a balance between social well-being, environmental responsibility, and economic growth. Rwanda is experiencing positive expansion, especially the city of Kigali is developing fast [4]. This project explores and evaluates tailored energy solutions for the district of Kicukiro, considering its opportunities and challenges.

2.3 Kicukiro

Kicukiro is the geographical boundary for the management project. It has approximately 490 000 inhabitants and holds an estimated population share of 28% in Kigali. Considering the district being one of the most urbanized in the area, it is additionally the most densely populated one [5]. With a total area of 166.7 km^2, the population density is approximately 2940 people/$km2$ [6]. In Kicukiro, the average income level per person is the highest compared to the other districts [7]. The airport of Kigali is located in Kicukiro and is in the process to be partially decommissioned, allowing only military flights [8]. This creates infrastructural opportunities in terms of renewable energy. A new airport will be operational by 2028 and will be located in Bugesera [9]. The district has relatively more flat land compared to Gasabo and Nyarugenge, which creates potential for new growth areas [7]. Popular tourist attractions such as Rwanda's art museum and Nyanza Genocide Memorial are located here as well.

Chapter 3

Current State

After a literature review, four sectors were found out to be the most relevant for Kicukiro: Energy and Electricity, Buildings, Cooking and Public Transport.

3.1 Energy and Electricity

Currently, around 76% of the population in Rwanda has access to electricity [10]. The objective for Rwanda is to achieve universal access to electricity, including off-grid solutions and grid extension [11]. There are plans to integrate more renewable energy into their mix. The government intends to expand solar, hydroelectric and methane gas projects and ensure that 60% of the total energy is generated by renewables [12]. By 2050, Rwanda aims to become a carbon-neutral economy. This emphasizes investments in green and sustainable infrastructure. However, to achieve the targets for the seventh sustainable development goal (SDG7 - affordable and clean energy), investments must be made [10].

Rwanda's current energy supply consists of coal, oil, natural gas, hydro and mainly biofuels and waste, which represents approximately 87,5% of the total supply. The generation of electricity is mainly contributed by hydropower, with 50,4%. Other sources of electricity generation are natural gas, oil, coal, and solar power, with their contributions in that specific order as well. Further details are shown in figure 2.1 and 2.2 below. The sector with the highest energy consumption in Rwanda is residential, which represents 80,7% of total consumption. The next most demanding sector is the transport system with 7,8%, and the industrial sector, which stands for approximately the same percentage [13].

Generally, there is higher electricity consumption in more urbanized areas due to better grid access. 57.7% of the Rwandan households are connected to the national grid and the majority is from urban areas. The electricity for Kicukiro is served by overhead power lines which depends on the national electricity supply [7][14]. The electricity access rate in Kicukiro is one of the highest in the entire country, it holds the share of 92.5%[15], which is higher than the national average which stands at 82.2% [14]. The higher income levels in Kicukiro could be an influencing factor, people tend to have more electrical appliances in urban areas which also increases the consumption of electricity.

Regarding the current state of the adoption of solar PV technologies at a district level, little to none documented information has been found. The Rwandan government has published a series of guidelines that regulate the installation of solar home systems, to enable a controlled adoption of small scale solar PV technologies [16]. Another indication regarding the possibility of an expansion of PV systems is found analysing the Rwandan energy tariffs, which starts from 89 RWF (0,06 USD) per kWh for households that consume less than 15 kWh per month, to 212 RWF (0,15 USD) per kWh if the limit is exceeded [17]. This encourages people and companies to rely on alternative electricity sources. Looking outside Kicukiro's geographical boundaries, there are documented plans for new PV installations, one of the most ambitious can be found in Gasabo district, where the "Green City Kigali" project has been launched including, within the measures considered, the installation of solar panels on residential units, demonstrating the positive intentions of the city's regulating authorities regarding the expansion of renewable solutions [18].

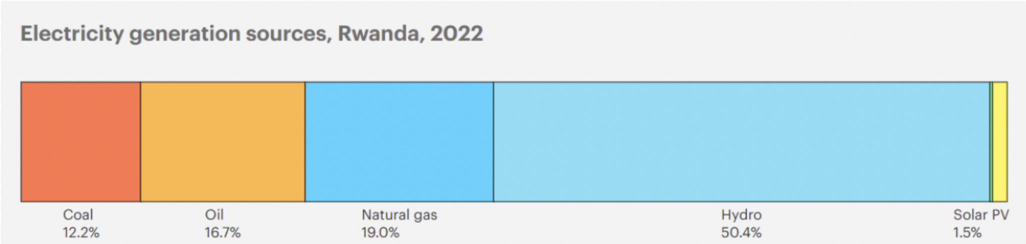


Figure 3.2: Rwanda's electricity mix [13].

Figure 3.1: Rwanda's Energy Supply [13].

3.2 Buildings

Although buildings have different roles in the urban environment, a detailed analysis of the diverse building typologies present in Kicukiro is provided in Section 4.3, this section focuses on the residential sector to evaluate the current building stock in Kicukiro. The main source for this evaluation is the Fifth Rwanda Population and House Census from 2022 [15], which provides disaggregated statistics of the number and distribution of private households; housing characteristics, including material types of the housing units, and infrastructure access.

Even though Kicukiro has a small percentage of rural areas, over 99% of households are situated in urban settings. The district contains a total of 135 463 private households with an average household size of 3.6 people per household, which is slightly above the average for the city of Kigali (3.5) but below the national mean (4.0). However, this average value differs between sectors. Kagarama and Nyarugunga have the highest average household size being 3.9 people per household, which suggests the extended presence of multigenerational family units. In contrast, Kicukiro sector has the lowest average size of household being 3.1 people per household, indicating smaller family units.

Habitat types across the district show that 61.8% of households live in modern planned urban housing, while 28.4% are located in spontaneous or squatter settlements. These two categories account for more than 91% in the urban sector of the district. In rural areas, by contrast, nearly all private households (87.1%) live in a planned rural settlement known as Umudugudu.

The materials used in the construction of the housing units provide detailed insight to the building's quality and socioeconomic conditions of the district. For roof construction, almost every housing unit (98.8%) is covered by iron sheets, which represents a substantial and positive difference of more than 24 percentage points compared to the national average in Rwanda (74.1%). Unlike roofs, walls and floor materials show more variation. Walls made by sun dried bricks with cement account for 62.7% of the total, followed at a considerable distance by burnt bricks of cement (11.3%). In terms of flooring construction, cements is the most common material, accounting for 62.7% of the total, although ceramic, clay and granite tiles are present in 22% of households in Kicukiro. Earth floors are substantially dominant in the rural areas, as they represent 67.4% of the household floor within this sector.

Access to basic infrastructure is another relevant factor when assessing the building characteristics of Kicukiro. Electricity is the main source of lighting, corresponding to 92.2% of the district households, closely aligned with the already mentioned 92.5% of electricity access share in Kicukiro. While the main source of lighting remains similar in urban areas, rural settlements show a significant contrast, as their main source of lighting is equally distributed between electricity (43.2%) and the use of flash-lights (42.6%). The heavy reliance on this last type of lighting source is linked to the fact that 82.5% of rural households in Kicukiro are not connected to the grid.

3.3 Public Transport

Most of the people living in Kicukiro have a maximum distance of 2 km from their school or workplace. Currently, most people are pedestrians or take the motorcycle or bus to their respective destination [7]. Rwanda's Ministry of Environment has established a national target to promote the adoption of electrified transportation as part of its broader strategy to achieve carbon neutrality by 2050. In particular, there is a strong emphasis on increasing the use of non-motorized and electric modes of transport, especially in densely populated urban areas such as Kicukiro. To support this transition, policies have been introduced to ensure that the cost of EV charging is aligned with the industrial electricity tariff, thereby enhancing the economic feasibility of electric vehicle use [19].

While much of the current momentum is focused on electric motorcycles, there is a growing interest in the electrification of the public bus fleet, which Rwanda aim to have 20% electrified by 2030 [20]. Buses play a vital role in Kicukiro's mobility system, and transitioning them to electric power would significantly reduce greenhouse gas emissions, lower operational costs, and improve urban air quality. This aligns with national efforts to modernize public transport infrastructure and integrate electric mobility into Rwanda's urban planning framework. However, the successful implementation of electric mobility depends not only on affordability and accessibility but also on improvements to road infrastructure. Road safety and development remain a concern, particularly for pedestrians and motorcycle users, due to several roads being discontinuous or poorly designed [7].

In recent years, several EV companies have been expanding their presence in the district. For motorcycles, innovative models such as the pay-as-you-drive system have made electric transport more accessible by charging users only for the energy consumed. Additionally, battery-swapping stations have been strategically deployed throughout Kicukiro to facilitate quick and convenient vehicle use [21]. This development is particularly relevant given the widespread use of motorcycle taxis—an affordable and commonly used form of transport in the district—most of which still rely on internal combustion engines [22]. The electrification of both motorcycles and buses represents a critical opportunity for Kicukiro to lead in the adoption of clean, sustainable, and inclusive mobility solutions. In this assessment, only the buses are accounted when calculating for the public transportation.

3.4 Cooking

The cooking sector is one of the most energy demanding in Rwanda, because of its reliance on biofuels [23]. In Kicukiro, the population uses mainly firewood and charcoal (71%), followed by liquified petroleum gas (26.2%) and electricity (0.1%) [15]. The poor LHV of these fuels and the inefficiency of the stoves lead to a high amount of cooking time and, therefore, to a high amount of energy. A study focusing on fuelwood use in Rwanda illustrates that improved cooking stoves reduce fuelwood use by 20%-56% and that 4 kg of firewood are burned per cooking session, compared to 1.2 kg of LPG, per person, every month [24]. The government is aware of the criticisms towards the use of biofuels, which are considered to be harmful especially for human health. Their combustion is highly inefficient and generates pollutants such as carbon monoxide, which are potentially deadly for living species. In addition, perplexities have arisen due to deforestation, environmental protection, and gender equality: since wood collection and cooking are traditionally assigned to women, they are more easily exposed to a higher amount of pollutants and potentially dangerous flue gases [23]. For these reasons, the government has improved the use of LPG and identified it as the most rapidly scalable solution for clean cooking. In 2020, it developed a National LPG Master Plan, with the support of the European Union and the German Development Bank. Some of the measures undertaken are payments models such as Pay-as-You-Go, which aims to increase the number of low-income households accessing LPG, directing public institutions to fully transition to LPG and expanding the market [25]. According to a study on access to clean cooking in Rwanda, the adoption of LPG in households is projected to increase, especially in urban settlements, reaching

86.4% of households in the city of Kigali by 2030 [26]. Other good solutions for clean cooking could be biogas-fuelled and electric stoves. In short, in addition to LPG, Rwanda Energy Group identifies biogas and electricity as the best alternatives to increase clean cooking to eliminate the use of firewood and charcoal. Biogas in particular seems to be an interesting opportunity for the circular economy of the district, as it can be produced from municipal solid waste, crops, agricultural waste that are gasified and turned into energy [23].

Chapter 4

Methodology

4.1 Our Vision

TekiniKicuckiro aims to create a nearly-zero-energy, people-oriented district, accounting for all the main energy-demanding parameters and sectors. Since Kigali's authorities are already working proficiently for a sustainable growth, a further push towards sustainability was performed, starting from existing policies and governmental directives. Developing a realistic assessment is the main objective and therefore every proposed solution has been evaluated and tailored for the district of Kicukiro.

4.2 Key Performance Indicators

The Key Performance Indicators are meant to be technical parameters to perform an even comparison between the different scenarios, in order to quantify how close to the proposed aims the results are. Therefore, five different KPIs are identified, three for the energy sector and two additional ones for the cooking and transport sectors.

4.2.1 Nearly zero energy KPIs

The first objective of the project is to progress towards a ”Nearly Zero” energy district. The idea behind it is to combine the evaluation of the total energy demand of the district with the share of renewables and self-sufficiency. This goal is therefore divided into three distinct KPIs.

KPI 1.1 - Total Annual Energy Demand

The total annual energy demand has to be evaluated for every sector considered. This KPI is necessary to track the energy efficiency and sustainability of the district's progress within the considered sectors.

$$\text{Total Energy demand of Kicukiro [kWh/year]} = \sum \text{(Energy demand of Kicukiro's sectors)}$$

KPI 1.2 - Share of Renewables

To have a complete assessment of the consequences of Kicukiro's energy system on the environment, it is important to quantify the impact of renewable energy generation technologies on the energy mix. A ”Nearly Zero” district should promote the shift towards decarbonization within every sector by enhancing the share of renewables.

$$\text{Share of Local Renewable Energy Generation [\%]} = \frac{\text{Renewable Generation}}{\text{Total System Load}} \cdot 100$$

KPI 1.3 - Self Sufficiency

The last KPI considered evaluates the production of energy within the district's boundaries. A self sufficient district is less reliant on external resources, enhancing energy resilience. This KPI, together with the previous ones, is necessary to have a complete evaluation of the district's energy situation.

$$\text{Energy Self Sufficiency [\%]} = \frac{\text{Self Supply}}{\text{Total System Load}} \cdot 100$$

KPI 2 - Share of Clean Cooking

Since one of the sectors accounted in all the scenarios is cooking, an evaluation of the households that adopted clean cooking has been done. For "clean" it is meant any stove using fuel that is not harmful for humans' health. Therefore, even LPG is considered clean although it emits carbon dioxide.

$$\text{Share of Clean cooking [\%]} = \frac{\text{Number of Households with Clean Cooking Access}}{\text{Total Number of Households}} \cdot 100$$

KPI 3 - Share of Green buses

The other sector accounted in all the scenarios is public transport, specifically buses. Every bus not fuelled by fossil fuels has been considered "green". The green buses are electricity or biogas fuelled vehicles.

$$\text{Share of Green buses [\%]} = \frac{\text{Number of Green Buses}}{\text{Total Number of Buses in the Fleet}} \cdot 100$$

4.3 System Mapping

The primary objectives of the system mapping are as follows:

- To present an accurate and detailed representation of the current energy situation in Kicukiro.
- To illustrate the interconnections between key factors that contribute to the overall measures and proposed solutions of the project.

To achieve this, a different approach to system visualization was sought: one that avoids the use of arrows, which may misleadingly suggest a simple cause-effect relationship. Given the complexity of the system, a more nuanced representation was necessary. The most effective structure for system mapping was determined to be a division into the four main sectors: Public transport, Energy, Buildings, and Cooking. The relationships between these sectors are represented through "islands" within the map, each occupying a defined space and shaded in different colours based on the areas they are associated with. Additionally, specific aspects within each sector are highlighted through bullet points.

At the centre of the map is the first set of Key Performance Indicators (KPIs 1.1, 1.2 and 1.3). This central positioning reflects its fundamental importance across all sectors and also serves as a connection between all of them. The second Key Performance Indicator (KPI 2), which addresses access to clean cooking, is relevant to the Cooking, Buildings, and Energy sectors, influencing each from both an energy and social perspective. The third and last Key Performance Indicator (KPI 3) is primarily associated with the Public Transport sector, as it is focused on green buses. However, it also extends into the Energy sector, given the intrinsic connection between transportation and its fuel energy sources. Regarding the different available energy sources, biogas will play a crucial role in the intersection of the Transport and Energy sectors and the intersection between Cooking and Energy.

Additionally, several boundary elements have been identified within the system, Power plants, which supply electricity to the city of Kigali, and therefore the district of Kicukiro. LPG and Biogas for cooking are outside the boundaries since they are external sources that need to be imported. Neighbouring districts, which may serve as potential collaborators but are not within the scope of this project. The city council is included as well, which plays a crucial role in policymaking and project regulations. However, as the project team does not hold decision-making authority in this area, the city council is placed outside the core system. Furthermore, waste treatment is highlighted as an integral element within the system, given its potential role as an energy source for generating heat and fuel for transportation. The representation of waste treatment within the system demonstrates its connection to KPI 1, as it has been considered part of the strategy to enhance sustainability in Kicukiro.

The system map below shows an approach that provides a comprehensive visualization of the interdependencies within the energy system, offering a holistic perspective on the pathways to achieve a more sustainable district.

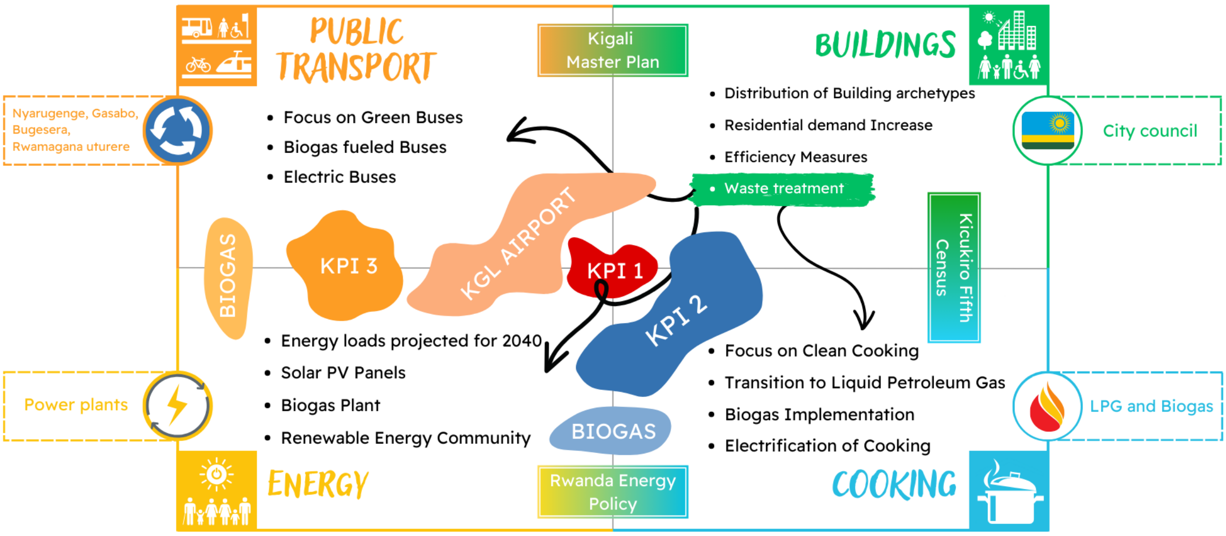


Figure 4.1: System Mapping of Kicukiro.

4.4 Scenarios

4.4.1 Scenario 1 - Business as usual (BAU)

For the business-as-usual scenario, the focus is posed on existing policies, future projections, and Kigali City's vision. Therefore, additional models are performed to understand how the existing policies would develop until 2040. The following decisions are undertaken for every sector.

- ENERGY: The main intention of Kigali's authorities is to complete the electrification of the city[27]. Currently, the Kicukiro electrification rate is 92.2 % (some rural areas are not yet electrified). Therefore, an electrification rate of 100% is assumed by 2030. However, since complete reliance on the grid, considering its instability, prices, and the spread of convenient technologies like PVs, seems unrealistic, a small amount of rooftop PVs is implemented just for a specific share of the high-income building archetypes (20 % of Hall, 15% of Villa and 15% of Mid-Rise).

- BUILDINGS: the archetypes distribution is kept constant throughout the years. A document describing the buildings archetypes loads is taken into account as a reference for business as usual loads [28]. The materials, insulation and equipment are kept as the IDA ICE workshop.

- COOKING: as previously explained, Kigali's government saw in LPG the main resource to reach a bigger expansion of clean cooking. A study focusing on clean cooking access in Rwanda predicts household

LPG adoption to be increased especially in urban settlements, reaching 86.4% of households in Kigali City by 2030 [26]. Therefore, this percentage is used in the model, the rest is assumed to be firewood and charcoal.

- PUBLIC TRANSPORT: as mentioned before, current policies in Rwanda aim to achieve a 20% share of electric buses within the total bus fleet by 2030 [20]. This target is maintained in the business-as-usual scenario and proportionally adapted to the context of Kicukiro. The additional buses introduced in the existing fleet during the following years are assumed to be electric.

4.4.2 Scenario 2 - Circular Economy (CE)

This scenario focuses on waste and waste-to-energy technologies to enhance sustainability and circular economy inside Kicukiro. The aim is to cope with waste management and energy needs at the same time, accounting waste as a useful source to power a sustainable city. Thus, organic waste is separated and collected in a biodigester to produce biogas. In this scenario the amount of biogas produced by the collected organic waste of Kicukiro is calculated, based on a research about waste-to-energy feasibility in Kigali [29]. Currently, the share of collected waste is 58% in Kicukiro [15].

- ENERGY: 100% electrification target is kept. To enhance sustainability and renewable energy in Kicukiro, the share of archetypes with rooftop PVs has been increased for Villas (50%), Mid-rise (50%) and Halls (50%). Additionally, PV panels are added to 20% of Bungalows.
- BUILDINGS: a bigger growth in the households energy demand is accounted for this scenario. Therefore, the loads are increased by 25%. Shadings are added to buildings with cooling demand (Villas, Mid-Rise and Bungalows).
- COOKING: the share of households using LPG is kept to 86.4%, with the rest being provided by biogas. Since the amount of biogas is not enough to power both the cooking and the transport sector, priority is given to the latter. Thus, the biogas used for clean cooking in this scenario needs to be imported.
- PUBLIC TRANSPORT: the objective for this sector is to integrate CNG-powered buses into the existing public transport fleet and to project the growth of this segment in the future development of Kicukiro. The biogas is entirely produced in Kicukiro, via biodigester and it is converted into CNG, which is then used as fuel. The amount of biogas-fuelled buses depends on the amount of fuel produced within the district.

4.4.3 Scenario 3 - Renewable Energy Community (REC)

The third scenario focuses on a broader electrification, that reaches different sectors and it is based on the implementation of a Renewable Energy Community (REC). Examples of REC are already present in Europe and they represent an innovative choice to spread the use of renewables, create social and economic value that is owned by the citizens themselves and protect the environment [30]. Additionally, this choice is tailored for the district, since the renewable energy is usually shared within the borders of an electric primary substation [31]. In this scenario, the implemented PV field produces energy that can be shared between the members of the REC. Additional information about the legislative and economic operation of a REC can be found in the Business Model Innovation section. For this scenario, extra attention was paid to the feasibility of the project and the measures adopted, trying to reach very realistic and pragmatic targets.

- ENERGY: the share of archetypes with rooftop PVs has been maintained. A shared solar PV field has been added in some areas that were identified as suitable in the partially decommissioned airport, with a total capacity of 27.46 MW.
- BUILDINGS: ideal coolers and shadings are added to two more archetypes (Halls and Blocks). The demand of every household is increased by 40%, following the projections performed by a study on Rwandan decarbonisation and scaled down to Kicukiro [32]. Finally, electric stoves are taken into account in the household's equipment electricity demand.

- COOKING: electric stoves are implemented in this scenario. Following the aforementioned document the most realistic path projects a share of 4.8% of households with electric stoves by 2040 [32]. The rest is considered to be fuelled with LPG.
- PUBLIC TRANSPORT: the aim in this scenario is to achieve 100% electrification of the public transport bus fleet by 2050, the yearly purchase of new electric buses is increased compared to the BAU scenario, replacing completely the existing diesel buses.

Chapter 5

Quantitative Modeling

In this chapter, every sector considered and every tool used for the quantitative modelling of Kicukiro are analysed. The assumptions and sources are stated, and the main calculations and values for each sector are presented. Since Kicukiro-produced biogas is required to supply the fuel needs of the transport sector in the "Circular Economy" scenario, it will be the first one to be discussed in the next paragraph. In the following sections, the evaluation of Public Transport and Cooking is reported, followed by the modelling process conducted with ArcGIS Pro, IDA ICE and HOMER Pro.

5.1 Biodigester

The calculations for the waste-to-energy process were made with the help of a document that focuses on solid waste management and waste-to-energy feasibility in Kigali [29]. Firstly, the amount of waste collected in Kicukiro has been evaluated. According to Kicukiro Fifth Census [15], The share of collected waste was 58%, in 2022.

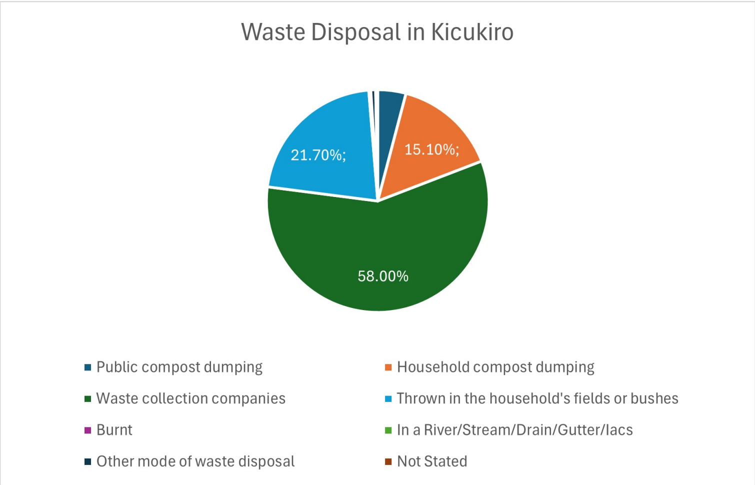


Figure 5.1: Waste Disposal in Kicukiro, in 2022.

Considering that by 2030, even the actual share of waste burnt and thrown to the environment will be collected, reaching a share of 88%, the calculations for collected waste were performed, based on the projected population of the district [33]. Every day, in Kigali, an average of 0,57 $kg/capita$ is produced and 70% of it is biowaste [29]. Biowaste is assumed to be completely collected and directed to the biodigester. The Hydraulic Retention Time (HRT) is 30 days. Using these values and assuming a water-to-substrate ratio of 1:1, the volume of the biodigester was found [29].

Table 5.1: Amount of biowaste in input to the biodigesters and volume required.

	2030	**2040**
Biowaste Input kg/day	240 343	345 930
Volume required m^3	14 421	20 756

Considered the total needed volume, three biodigesters of 10 000 m^3 capacity will be purchased, to cover a future increase in the collected waste projected for 2050. With a biogas yield of 0.35 m^3/day [29], the final amount of biogas produced is the following:

Table 5.2: Biogas output.

	2030	**2040**
Biogas Output Kg/day	17 406,98	25 054,18

5.2 Public Transport Sector

In the transport sector, the project focused on the existing public bus fleet in Kicukiro. The total number of public buses projected for Kigali in 2025 is 500 units according to Kigali's KT Press [34], including both medium-sized buses (approximately 8 meters in length) and large buses (12 meters in length). This was proportionally adjusted based on the population number in Kicukiro in 2025, resulting in an estimated fleet of 140 public buses.

Projections for the total number of buses in 2030 and 2040 were also based on population growth and applied across all scenarios. It was assumed that each bus travels an average of 164 kilometers per day [35].

The annual diesel consumption (kWh/year) calculated using the equation below, was compared with the energy consumption of green alternatives in each scenario. This comparison was carried out by converting diesel consumption, initially provided in liters per kilometer, into kilowatt-hours per year:

$$\text{Energy Consumed [kWh/year]} = \text{Energy content in fuel} \cdot \text{Distance per year} \cdot \text{Diesel consumption} \quad (5.1)$$

Where:

- Fuel Consumption (L/100 km) refers to the average fuel usage of the bus, specific to its type (12.5 L/100 km for 7-meter buses [36], and 46.1 L/100 km for 12-meter buses [37]),
- Daily Distance is 164 km [35],
- Energy Content of Diesel is 10.01 kWh/L, calculated based on a diesel density of 0.846 kg/L and a Lower Heating Value (LHV) of 11.83 kWh/kg [38].

The results presented in Table 5.3 refer to the annual energy consumption of a single bus. The total yearly consumption for the entire fleet will be evaluated and compared across each scenario.

Table 5.3: Energy Consumption of a single Diesel Bus.

	Large Bus	**Medium Bus**
Yearly Consumption [kWh/year]	74 886.21	276 180.33

5.2.1 Scenario 1 - Business as usual

For Scenario 1 - BAU, Rwanda's 2030 target of achieving a 20% share of electric buses was taken into account [39]. 20% of the total bus fleet was designated as electric. As shown in Table 5.4, this results in 34 out of the projected 172 buses in 2030 being electric.

Table 5.4: Evolution in the number of electrical buses concerning the total number of buses for Scenario 1.

	2025	**2030**	**2040**
Total Number of Buses	140	172	247
Number of Electrical Buses	-	34	110

For the 2040 projections, it was assumed that all additional buses introduced between 2030 and 2040 would be electric. This assumption accounts for the increase in the number of electric buses observed between these years[40].
Based on the projected number of buses, an assessment of the corresponding electrical load is shown in Equation 5.2.

$$\text{Demand [kWh/year]} = \frac{\text{Battery Storage}}{\text{Battery Range}} \cdot \text{Distance} \cdot 365 \tag{5.2}$$

For modelling purposes, parameters such as bus type, passenger capacity, battery range, and battery capacity were derived from the specifications of the new electric buses introduced in Kigali as of December 2023 [41].

- Battery Storage is 280 kWh
- Battery Range is 300 km
- Distance was designated as stated before

The demand obtained for 2040 was compared to the one of diesel buses, as demonstrated in the table below:

Table 5.5: Comparison of yearly consumption between Electrical Buses and Diesel Buses.

	2040
Electrical Buses Yearly Consumption [kWh/year]	6 145 628.50
Diesel Bus Yearly Consumption (Large+Medium) [kWh/year]	27 570 705.00

The results reveal that electric buses are projected to require approximately 6 145 628.50 kWh/year, while diesel buses would consume around 27 570 705.00 kWh/year.
This reduction, demonstrates the higher efficiency of electric vehicles compared to internal combustion engines buses. Despite differences in energy sources and technologies, this advantage makes electric buses a highly effective solution for reducing overall energy demand in the public transport sector.

5.2.2 Scenario 2 - Circular Economy

In the second scenario, biogas (which is converted into compressed natural gas) was introduced as the fuel source, replacing electricity in public transport, as previously described in the report. As shown in Table 5.6, the total number of buses is consistent with the projections made before. However, the calculation of the bus share differs in this context: the share of buses operating on CNG was determined based on the volume of biogas produced by the biodigester implemented in the scenario, assuming that the entire biogas output would be exclusive for bus operation.
To determine the quantity of CNG required for one single bus to cover the specified distance in a year, the following equation was applied:

$$\text{Bus consumption}[m^3/day] = \text{Distance per year} \cdot \text{CNG Consumption} \cdot \text{Density} \tag{5.3}$$

Where it was assumed that:

- CNG Consumption (kg/km) is 0.5 m^3/km [42]
- Density is 1.22 kg/m^3

Using these values for a single bus, it was then possible to scale the calculation according to the share of the existing public buses in Kicukiro that could operate on CNG, previously calculated.

Table 5.6: Evolution in the number of biogas buses concerning the total number of buses for Scenario 2.

	2025	**2030**	**2040**
Total Number of Buses	140	172	247
Number of Biogas Buses	-	95	136

The yearly energy consumption was then converted into kilowatt-hours per year (kWh/year) using the Lower Heating Value (LHV) of biogas, which was determined to be 6 kWh per cubic meter (m^3)[29]. This conversion was applied to each bus, as indicated in Table 5.6. Finally, a comparison between the yearly consumption of each type of bus.

Table 5.7: Comparison of yearly consumption of Biogas buses with Diesel buses.

	2040
Biogas Bus Yearly Consumption [kWh/year]	29 679 562,57
Diesel Bus Yearly Consumption (Large+Medium) [kWh/year]	20 390 016,40

The higher energy consumption of biogas buses appears to be at a disadvantage. However, biogas is locally produced in this case, forming part of a circular economy model, making it possible to reduce reliance on external energy sources and minimizing the environmental impact that diesel has.

5.2.3 Scenario 3 - Renewable Energy Community

For this scenario, the objective was to achieve a 100% electrified public bus fleet in Kicukiro by 2050. To reach this target, a linear regression was applied to estimate the share of electric buses over time. Based on this approach, the following key values were obtained for the number of electric buses in operation in the years 2030, 2040, and 2050:

Table 5.8: Evolution in the number of electrical buses concerning the total number of buses for Scenario 3.

	2025	**2030**	**2040**	**2050**
Total Number of Buses	140	172	247	336
Number of Electrical Buses	-	95	136	336

To calculate the electrical load, the same logic applied in Equation 5.2 from Scenario 1 was used. This approach estimated the total yearly energy consumption for the projected electric bus fleet. The values are presented in Table 5.9, and compared with the corresponding diesel bus energy demand.

Table 5.9: Comparison of yearly consumption of Electrical buses with Diesel buses.

	2040
Electrical Buses Yearly Consumption [kWh/year]	10 335 829.75
Diesel Bus Yearly Consumption (Large+Medium) [kWh/year]	6 857 180.19

The higher total energy consumption of the electric fleet may appear too high, especially considering the typically higher efficiency of electric drivetrains. However, this result is explained by the larger number of buses operating under the electrification strategy. While individual electric buses consume less energy per kilometer compared to their diesel counterparts, the overall fleet size increase leads to a higher cumulative energy demand.

5.3 Cooking Sector

The cooking sector was analysed and evaluated in different years and scenarios. The growth in the number of households has been calculated based on the projected population growth. Official data from the National Institute of Statistics of Rwanda were found about Kicukiro population growth [33], since the document had projections until 2032, these were linearly increased until 2050. Then, the number of people per household was found and projected until 2050, and combining these two data, the number of households for every year was calculated. Finally, the use of one stove per household and a total of 2.5 cooking sessions per day were assumed. The measures taken are analysed for each scenario.

5.3.1 Scenario 1 - Business as Usual

In this scenario, according to projections found in a document on universal access to clean modern energy in Rwanda[26], the use of LPG is expected to reach 86.4% of the households in Kigali City by 2030 and the same share was kept for Kicukiro, while the rest is assumed to be fuelled by firewood and charcoal. For 2040, the share of households using LPG was linearly increased, reaching 93.2 % and the rest was still considered to be biomass. To account for the energy demands of the cooking sector the following information about the aforementioned fuels were researched (charcoal was converted into firewood, since the production of 1 kg of charcoal requires 4 kg of firewood [43] [44]).

Table 5.10: Firewood characteristics.

Kg of firewood per cooking session	Firewood LHV
4	16 MJ/kg

Table 5.11: LPG characteristics.

Kg of LPG per person per month	LPG LHV
1.2	12.64 kWh/kg

With this information, the total amount of energy demand in one year for the cooking sector was calculated.

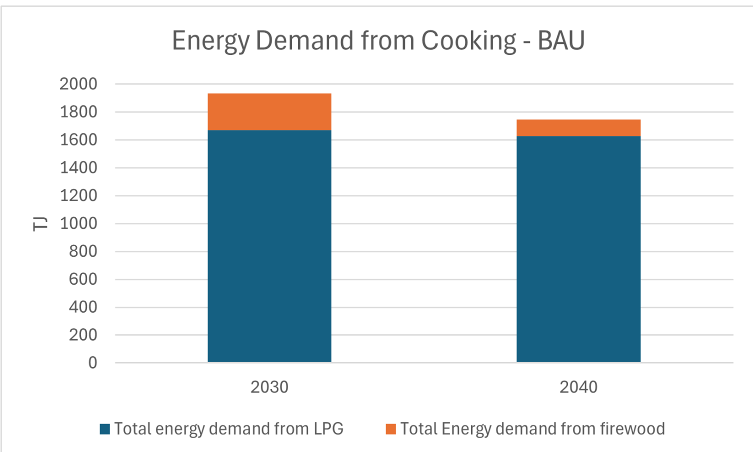


Figure 5.2: Total energy demand from cooking sector for 2030 and 2040 - BAU.

5.3.2 Scenario 2 - Circular Economy

The "Circular Economy" scenario uses biogas and LPG as sources for the cooking sector. The share of households using LPG has been kept to 86.4 % for every year starting from 2030, the rest is biogas. In this way, the number of households will increase, but the share of them using biogas or LPG will remain unchanged. Since the projected biogas production in Kicukiro is not enough to satisfy both the cooking and the transport sectors' demand, the latter has been prioritized. The biogas resource needs to be imported from outside Kicukiro's boundaries. The biogas characteristics are as follows [45] [46] [29].

Table 5.12: Biogas Characteristics.

Biogas Consumption	Cooking time per session with biogas	LHV Biogas
0,35 m^3/hour	66 min	17788. 24 kJ/kg

With this information the total amount of energy demand, in one year, from the cooking sector was calculated.

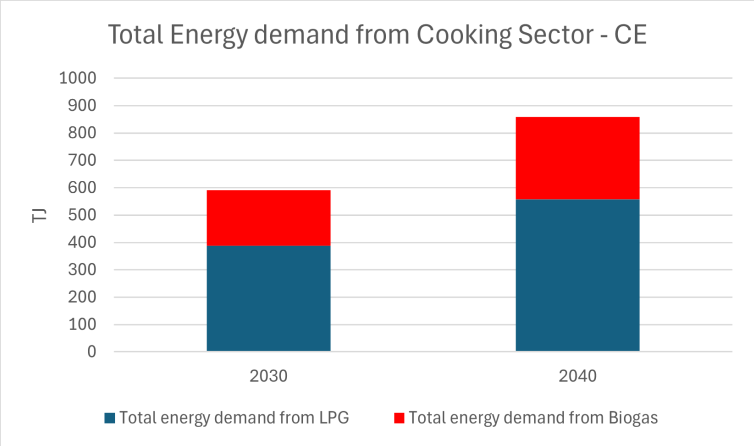


Figure 5.3: Total energy demand from cooking sector for 2030 and 2040 - CE.

5.3.3 Scenario 3 - Renewable Energy Community

For the "Renewable Energy Community" scenario, the research was based on a document from Sidney University with the collaboration of the Institute for Sustainable Futures [32]. Here, the number of households in Rwanda that use electric stoves is evaluated both for 2030 and for 2040. These values were scaled down to Kicukiro. From the cooking point of view, this scenario has a more conservative nature compared to the other two. The percentages of households using the different cooking fuels are as follows for 2030 and 2040.

Table 5.13: Percentages of households using different fuels in 2030.

2030	Households (%)
LPG	52.4%
Electricity	0.8%
Firewood	46.8%

Table 5.14: Percentages of households using different fuels in 2040.

2040	Households (%)
LPG	95.2%
Electricity	4.8%
Firewood	0%

Finally, the total energy demand for the cooking sector has been evaluated for one year.

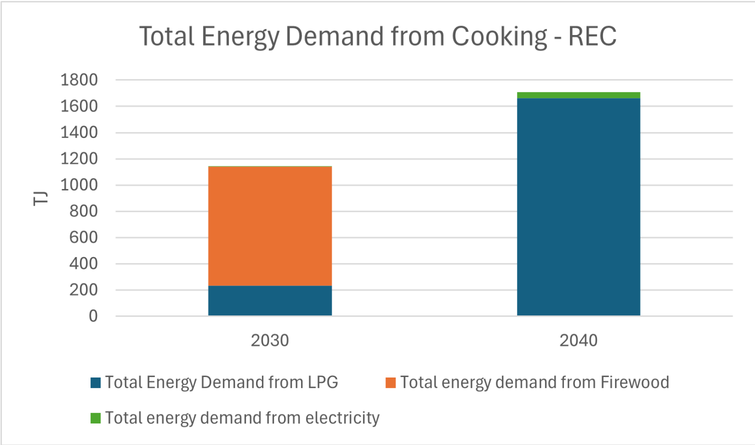


Figure 5.4: Total energy demand from cooking sector for 2030 and 2040 - REC.

5.4 ArcGIS Pro

ArcGIS Pro was used to extract and analyse the relevant building dataset for this project, focusing on spatial information related to the building energy modelling. The building dataset used, provided as an ESRI polygon shapefile, belongs to the article by Bachofer et al. (2019), Building Stock and Building Typology of Kigali, Rwanda [47], which employed very high-resolution Pléiades imagery to map building footprints, archetypes and heights in central Kigali for the year 2015. The dataset includes detailed morphological data and change detection analysis at the building level. Using ArcGIS Pro, the 2015 building archetype distribution in Kicukiro district was extracted, allowing for the identification of the different building typologies, together with the average floor area and height. These spatial insights not only revealed the most common building archetypes in the district but also helped in the modelling of the building archetypes for the calculation of the buildings' energy performance in IDA ICE.

Figure 5.5: Sample section of the Shapefile showing different building archetypes in Kicukiro.

After importing the dataset into ArcGIS Pro, the shapefile was edited to focus exclusively on the Kicukiro district. This was achieved using the "Clip" geoprocessing tool, which extracted only the features within the administrative boundary of Kicukiro. The boundary shapefile used for this operation was sourced from official data provided by the Rwanda Land Management and Use Authority (RLMUA) and the National Institute of Statistics of Rwanda (NSIR). Once clipped, the updated shapefile included only the buildings located within the Kicukiro district boundaries in 2015. From this processed dataset, the total number of buildings per archetype was extracted, together with their average height and floor area, which served as the basis for selecting the most representative building archetypes to be considered in the remainder of the project, which are presented below:

Table 5.15: Representative building archetypes in Kicukiro.

Archetype	Number of Buildings (2015)	Building Average Height (m)	Building Average Floor Area (m^2)
1 Basic	46 082	2.4	65.2
2 Block	315	2.7	141.0
3 Bungalow	11 278	3.6	176.7
4 Villa	2 087	4.5	270.3
5 Mid-rise	184	5.1	619.0
7 Hall	1 726	3.8	566.8

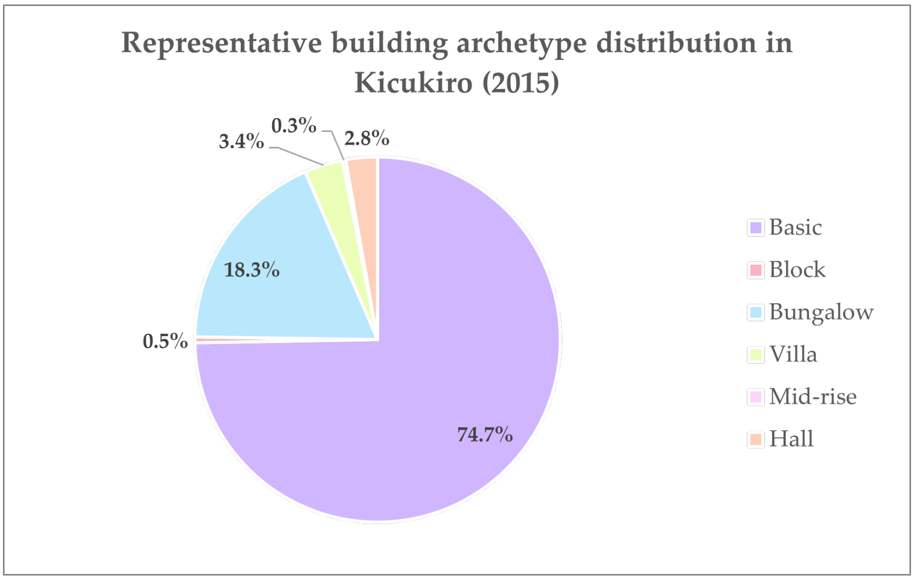


Figure 5.6: Representative building archetype distribution in Kicukiro for 2015.

For the purposes of this project, it was assumed that the distribution of building archetypes in 2015 remains unchanged in all future projections considered within each of the defined scenarios.

5.5 IDA ICE

The energy performance of the buildings in Kicukiro district was assessed using the building performance simulation software IDA Indoor Climate and Energy (IDA ICE), developed by EQUA Simulation AB. This simulation tool was used to model the energy demand of the six building archetypes analysed in the project, as defined in Section 4.2, with each archetype adapted to its specific geometry, construction characteristics and average electricity consumption. The average consumption values for the Basic, Bungalow and Villa building archetypes in Scenario 1 were based on the values from the study by Uwera et al. (2023), Bottom-up assessment of household electricity consumption in dynamic cities of the Global South—Evidence from Kigali, Rwanda [28], which adopts the same building typology definitions as those established by Bachofer et al. (2019) [47]. The software also enabled the modelling of energy saving measures and projected variations in electricity consumption implemented in Scenarios 2 and 3.

The average floor area and building height for each archetype were adapted from the mean values identified through the analysis of the shapefile in ArcGIS Pro. The number of occupants assigned to each building archetype was based on the occupancy assumptions presented during the IDA ICE workshop session.

Table 5.16: Parameter values for height, floor area and occupancy used in IDA ICE based on the shapefile average values.

Archetype	1	2	3	4	5	7
Building Average Height (m)	2.4	2.7	3.6	4.5	5.1	3.8
Modelled Building Height (m)	2.5	2.5	3.5	5	5	4
Number of Floors per Building	1	1	1	2	2	1
Building Average Floor Area (m^2)	65.2	141.0	176.7	270.3	619.0	566.8
Modelled Building Floor Area (m^2)	65	140	175	270	620	570
Number of Occupants per Building	4	5	5	10	100	35

The construction characteristics for each building archetype were defined according to the guidelines presented during the IDA ICE workshop session. These guidelines were themselves based on the construction assumptions and typological classifications outlined in Bachofer et al. (2019)[47].

Table 5.17: Elements of construction U-values (W/m^2·K) used to model the building archetypes in IDA ICE.

Archetype	1	2	3	4	5	7
External Walls (W/m^2·K)	2.65	2.3	2.02	2.02	2.02	2.3
Internal Walls (W/m^2·K)	1.71	1.71	1.71	1.71	1.71	1.71
Internal Floors (W/m^2·K)	0.16	0.16	0.16	0.16	0.16	0.16
Roof (W/m^2·K)	4.36	1.27	1.27	1.27	0.33	1.27
External Roof (W/m^2·K)	2.97	2.9	2.9	2.9	2.9	2.9
Glazing	© 1 pane glazing, clear, 4					

Following the modelling of the building archetypes and the assessment of their energy performance, the annual hourly energy loads, defined in terms of electricity purchased by facility, were exported to be used as input data in HOMER Pro. These energy loads include the electricity demand of equipment and lighting, as well as that of the ideal coolers and HVAC systems in those archetypes equipped with such systems.

5.5.1 Internal gains

Internal gains in IDA ICE refer to the heat generated within a building zone by sources other than the thermal conditioning systems. These include metabolic heat from occupants, electrical equipment such as appliances and electronic devices, and lighting.

Occupants

Internal gains from occupants come from their metabolic activity, which generates heat within indoor spaces. In IDA ICE, these gains are defined by the number of occupants, the designated schedule and their activity level (metabolic rate) and clothing insulation. The following table summarises these parameters for each building archetype:

Table 5.18: Parameters for Occupant internal gains by building archetype in IDA ICE.

Archetype	1	2	3	4	5	7
Number of Occupants per Building	4	5	5	10	100	35
Schedule	© House living (example) (7 Hall © 07 - 17 Weekdays)					
Activity level (MET)	1.0					
Clothing (CLO)	Constant: 0.85 ± 0.25					

The number of occupants per building archetype and their associated parameters were kept constant in all three scenarios.

Equipment and Lightning

Equipment and lighting contribute to internal heat gains in buildings, affecting both electricity demand and indoor thermal conditions. In IDA ICE, these gains are defined by usage schedules and power densities, specific to each building archetype. The following table outlines the equipment and lighting schedules and power densities applied across the three scenarios:

Table 5.19: Parameters for Equipment and Lighting internal gains by building archetype in IDA ICE.

	Archetype	1	2	3	4	5	7
Scenario 1	**Equipment Power density (W/m^2)**	1.5	1.8	4	0.5	5	50
	Equipment Usage Schedule	© House lighting (7 Hall © 07 - 17 Weekdays)					
	Lighting Power density (W/m^2)	1.5	3	3	0.75	3	10
	Lighting Usage Schedule	© House lighting (7 Hall © 07 - 17 Weekdays)					
Scenario 2	**Equipment Power density (W/m^2)**	1.88	2.25	5	0.625	6.25	62.5
	Equipment Usage Schedule	© House lighting (7 Hall © 07 - 17 Weekdays)					
	Lighting Power density (W/m^2)	1.88	3.75	3.75	0.94	3.75	12.5
	Lighting Usage Schedule	© House lighting (7 Hall © 07 - 17 Weekdays)					
Scenario 3	**Equipment Power density (W/m^2)**	2.06	1.8	5.5	0.69	6.88	50
	Equipment Usage Schedule	© House lighting (7 Hall © 07 - 17 Weekdays)					
	Lighting Power density (W/m^2)	2.06	3	4.13	1.03	4.13	10
	Lighting Usage Schedule	© House lighting (7 Hall © 07 - 17 Weekdays)					

5.5.2 Thermal conditioning systems

In IDA ICE, thermal conditioning systems regulate indoor air temperature through either simplified or detailed models. Depending on the scenario, two types of systems were applied to certain building archetypes: the Ideal Cooler and the HVAC system. The Ideal Cooler is a theoretical and simplified model that provides the exact amount of cooling required to meet the temperature setpoint, which was set in every zone to be 21ºC and 26ºC for the minimum and maximum temperatures, respectively. In contrast, the HVAC system represents a more detailed and realistic setup. In this project, the HVAC setpoint for supply air temperature was set to 16ºC, with no heat exchanger effectiveness. These systems were assigned to specific building archetypes across the three scenarios, as described in the following table:

Table 5.20: Thermal conditioning systems assigned to each building archetype per scenario in IDA ICE (n/a = not applied).

	Archetype	1	2	3	4	5	7
Scenario 1	**Ideal Cooler**	n/a	n/a	Yes	Yes	Yes	n/a
	Standard Air Handling Unit (CAV: 1 L/s·m^2)	n/a	n/a	n/a	n/a	Yes	n/a
Scenario 2	**Ideal Cooler**	n/a	n/a	Yes	Yes	Yes	n/a
	Standard Air Handling Unit (CAV: 1 L/s·m^2)	n/a	n/a	n/a	n/a	Yes	n/a
Scenario 3	**Ideal Cooler**	n/a	Yes	Yes	Yes	Yes	Yes
	Standard Air Handling Unit (CAV: 1 L/s·m^2)	n/a	n/a	n/a	n/a	Yes	n/a

5.5.3 Energy efficiency measures

A single but effective energy efficiency measure was evaluated in the project: the addition of external shading devices, specifically drop arm awnings, which deploy when direct sunlight strikes the building's windows. This energy efficiency measure was applied only to building archetypes equipped with Ideal Coolers, starting from Scenario 2, while Scenario 1 served as the baseline without any shading. The aim of this energy efficiency measure was to reduce electricity demand associated with cooling by limiting solar heat gains and lowering indoor temperatures.

Table 5.21: Energy efficiency measure (drop arm awnings) applied to each building archetype per scenario in IDA ICE (n/a = not applied).

	Archetype	1	2	3	4	5	7
Scenario 1	**External shading**	n/a	n/a	n/a	n/a	n/a	n/a
Scenario 2	**External shading**	n/a	n/a	Yes	Yes	Yes	n/a
Scenario 3	**External shading**	n/a	Yes	Yes	Yes	Yes	Yes

5.6 HOMER Pro

The electricity supply of Kicukiro has been modelled with HOMER Pro, developed by UL Solutions. The software is designed for the optimization of microgrids, extensively used to design and simulate the energy and economic performance of smaller systems, such as islands and campuses. Its flexible nature and its scalability has permitted to carry out a district-wide analysis.

HOMER Pro has been used to evaluate the electrification of the buildings and the electric vehicles considered within our system's boundaries. Different solutions have been considered for every scenario, in terms of technologies and capacities, to evaluate their yearly performance and to find the optimal solution between the calculated simulations. In the following sections it is presented a description of the modelling process.

5.6.1 Loads

The first step to start the analysis has been to implement the electricity loads of the Building and Transport sectors for 2040 (representing an average between 2030 and 2050), which differ between each other depending on the scenarios considered. For this reason, three different models have been prepared and separately evaluated.

Buildings

The single buildings' load has been calculated using IDA ICE and it was then amplified through post-processing, by adding up every single archetype considered within the district. In the table below the daily load of the buildings is reported.

Table 5.22: Daily Load and Peak Load for every scenario's buildings.

	Daily Load [kWh/d]	**Peak demand [kW]**
1-BAU	732 665.76	161 000.00
2-CE	780 069.84	143 000.00
3-REC	850 881.36	152 000.00

Electric Buses

The electric buses' load has been manually modelled. Following the calculations that have been done for the Transport's modelling, the daily load of a single electric bus is 153.3 kWh. A load for a single bus during the year has been created following these assumptions:

Table 5.23: Charging routine and hourly load for a single bus.

Electric bus	
Hours of Charging	22:00 - 04:00
Hours of Operation	05:00 - 21:00
Hourly load [kWh]	21.9

Using Excel, the hourly load has been randomized to have a more realistic demand, with an assumed Day-to-day variability of 7% and a Timestep variability of 1.5%.
The load of a single bus has been then amplified to represent the total electrified fleet.

The table and the image below represent the total load of e-buses for the three scenarios considered and their hourly load for a single day.

Table 5.24: Daily Load and Peak Demand for every scenario's e-buses.

	Daily Load [kWh/d]	**Peak Demand [kW]**
1-BAU	16 869.97	3 016.89
2-CE	\	\
3-REC	28 497.72	5 198.03

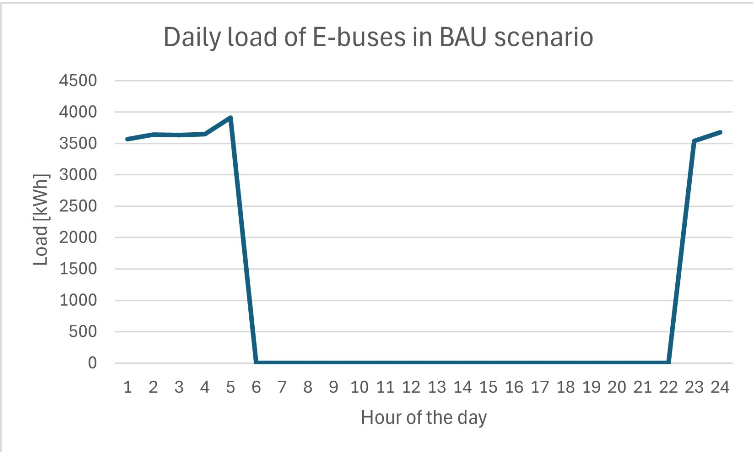


Figure 5.7: Daily load for the E-buses fleet in BAU scenario.

5.6.2 Technologies

For Kicukiro's electrification, different options have been considered, based on the scenarios created and their relative chosen measures. Below, it is reported a list of the technologies included in the modelling, and the chosen parameters that were given as an input to HOMER Pro.

Grid

The electric grid is the first technology that has been modelled. It plays a crucial role for the district's electrification, in every single scenario considered. The system relies on the grid for the electricity that is not produced by other sources, providing power to the Buildings' and E-buses' loads. In the following table the key input parameters for Kicukiro's grid are reported. The Kicukiro's grid renewable fraction is 80% (Project Description).

Table 5.25: HOMER Pro's input parameters for the electricity grid. The grid's modelling is the same in every scenario considered.

Input Parameter	Value	Source
Grid Power Price [USD/kWh]	0.24	Project Description
Grid Sellback Price [USD/kWh]	0.00	Assumption
Carbon Dioxide [g/kWh]	40.00	Project Description

PV panels

Due to Kicukiro's high solar potential, PV panels are included in every scenario considered. In total, three different typologies of PVs have been included. Regarding the panels' size and capacity, the reference PV model used is the Vertex S N-type i-TOPCon, produced by Trinasolar [48].

Table 5.26: Description and technical parameters of the PV considered.

PV type:	Description	Size of a single panel [m2]	Single Panel Capacity [kW]
Residential	Rooftop PV mounted on "Bungalow" and "Villa" archetypes	1.96	0.415
Commercial	Rooftop PV mounted on "Hall" and "Mid-rise" archetypes	1.96	0.415
Ground Mounted	Ground mounted PVs on the partially-decommissioned Kigali International Airport	1.96	0.415

Regarding the investment and O&M costs, due to the scarcity of recorded values and projections for the Rwandan market, the estimation has been based on the prices of South African's utility-scale PV panels for 2023, accounting for installation costs and inverters [49]. The price has then been projected for 2030 and the variation in price between the three PV typologies, along with O&M prices as a fraction of the CAPEX, have been defined based on the "moderate scenario" projections and price differences between the PV panels typology in the United States [50].

Table 5.27: PV panels' CAPEX and OPEX.

PV type:	CAPEX [USD/kW]	OPEX [% of CAPEX]
Residential	1 644.75	1.16
Commercial	1 021.00	1.06
Ground Mounted	930.00	1.5

As an input parameter for an HOMER Pro optimization, it is necessary to define a "search space" for every adopted technology. The search space has been defined by selecting a maximum capacity for every type of panel and by creating a list of intermediate capacities to simulate. The definition of the upper limit of the search space for "residential" and "commercial" panels is based on the maximum load of each archetype in 2030 and their available roof area. The number of PVs mounted on each archetype should be enough to supply their maximum load. If the available roof space of every building is less than the required area to satisfy the load, the number of PVs is reduced to the maximum amount that can be installed.

Table 5.28: Available rooftop area and maximum theoretical amount of panels.

Archetype	Rooftop Area [m2]	Available Area [m2]	Max # of Panels	Available area [% of Rooftop Area]
Bungalow	178.47	44.62	22	25 [51]
Villa	270.29	67.57	35	25 [51]
Mid-Rise	619.04	154.76	79	25 [51]
Hall	566.75	340.05	190	60 [51]

Table 5.29: Number of PVs on each archetype and maximum installed capacity for "Business as Usual" scenario (Residential PV = 2 963.72 kW, Commercial PV = 4 780.55 kW).

Archetype	Maximum Load [kW]	# of PVs	# of buildings	Share of buildings with PVs [%]	Total PV capacity [kW]
Bungalow	1.82	5	28 587	0	0
Villa	3.694	9	5 290	15	2 963.72
Mid-Rise	21.55	52	467	15	1 511.68
Hall	3.42	9	4376	20	3 268.87

Table 5.30: Number of PVs on each archetype and maximum installed capacity for "Circular Economy" scenario (Residential PV = 16 076.9 kW, Commercial PV = 14 833.3 kW).

Archetype	Maximum Load [kW]	# of PVs	# of buildings	Share of buildings with PVs [%]	Total PV capacity [kW]
Bungalow	1.418	4	28 587	20	9 490.88
Villa	2.417	6	5 290	50	6 586.05
Mid-Rise	20.5	50	467	50	4 845.12
Hall	4.275	11	4 376	50	9 988.22

Table 5.31: Number of PVs on each archetype and maximum installed capacity for "Renewable Energy Community" scenario (Residential PV = 16 076.9 kW, Commercial PV = 15 935.2 kW).

Archetype	Maximum Load [kW]	# of PVs	# of buildings	Share of buildings with PVs [%]	Total PV capacity [kW]
Bungalow	1.482	4	28 587	20	9 490.88
Villa	2.254	6	5 290	50	6 586.05
Mid-Rise	21.3	52	467	50	5 038.93
Hall	4.586	12	4 376	50	10 896.24

The "Renewable Energy Community" scenario is the only one in which ground-mounted PVs are considered. The maximum available capacity has been estimated by considering the maximum available space of the airport area, calculated with Google Earth. To define a relation between space and installed capacity, a power density of 0.35 [MW/acre] has been chosen (1 acre corresponds to 4 046.86 m2), [52].

In the image below, the portions chosen for the PV installation are highlighted.

Figure 5.8: PV installation within Kigali International Airport.

Table 5.32: PV capacity installed in every airport area. Maximum capacity of the installation: 27.46 MW.

Location	Total Area [m2]	Total Area [acres]	Max Capacity [MW]
Northwest Grass (1)	60 000	14.82	5.19
Apron (2)	62 500	15.44	5.4
Northeast Grass I (3)	95 000	23.47	8.22
Northeast Grass II (4)	100 000	24.71	8.65

The additional parameters chosen for every type of PV is reported in the following table:

Table 5.33: PV panels' additional parameters.

Ground Reflectance [%]	20	Assumption
Panel Slope [deg]	6	SOURCE: [53]
Panel Azimuth [deg]	180	SOURCE: [53]
Lifetime [years]	25	Assumption
Tracking System	No Tracking	Assumption
Temperature Effect	Yes	Assumption
Efficiency at STC [%]	18	Assumption
Derating Factor [%]	80	Assumption

Converter

A converter is added to convert DC solar-generated electricity to AC, to satisfy the selected loads. The investment cost of the photovoltaic modules, defined in the previous sections, includes the cost of the inverters. The selected model is the "generic large, free converter", with an assumed efficiency of 95%.

Battery

An electrical storage option has been considered only for "Renewable Energy Community" scenario. The addition of a BESS technology enhances the flexibility of the energy system, enabling the storage of PV-generated electricity, increasing the system's net renewable fraction and its self-sufficiency.

Table 5.34: Techno-economical parameters for the chosen battery module in the "Renewable Energy Community" scenario.

Model:	Generic 1 MWh Li-Ion
CAPEX (USD/module)	330 000.00 [54]
OPEX (USD/module)	8 250.00 [54]
REPLACEMENT (USD/module)	260 000.00 [54]
Roundtrip Efficiency [%]	90 (Assumed)
Lifetime [years]	15 [54]

For the batteries' search space, the assumed upper limit is set to 100 MWh, corresponding to 100 modules.

5.6.3 HOMER Pro additional parameters

The final step before starting the simulations has been to define the economic indicators for the analysis, its boundaries, and its system's control logic.

Table 5.35: HOMER Pro's additional input parameters for every scenario.

Nominal Discount Rate [%]	8	Project Description
Expected Inflation Rate [%]	5	Project Description
Project Lifetime [Years]	20	Project Description
Currency	USD	\
System Fixed CAPEX (USD)	0.00	Assumption
System Fixed OPEX (USD/year)	0.00	Assumption
Minimum Renewable Fraction [%]	0.00	\
System's Control Logic	HOMER Load Following	\

Chapter 6

Results

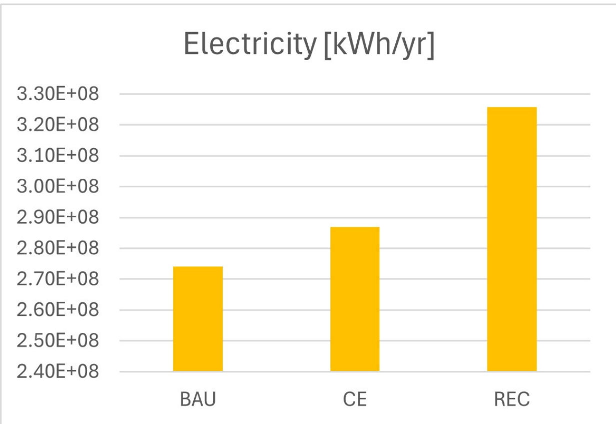
6.1 KPIs

Following the quantitative modeling of Kicukiro's system, an evaluation has been done on the projected results for the chosen KPIs. KPIs 1.1, 1.2 and 1.3 have been evaluated for 2040, while KPIs 2 and 3 for 2030 and 2040, in order to have a representation on the systems's evolution during the years.

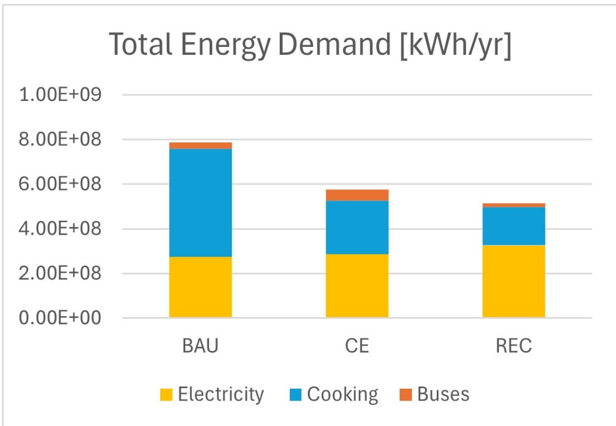
6.1.1 KPI 1 - Nearly Zero Energy

KPI 1.1 - Total Annual Energy Demand

The evaluation of the district's total energy demand has been done including every single sector considered, in the following graphs the total electricity and the total energy consumption are reported.



(a) Electricity demand.



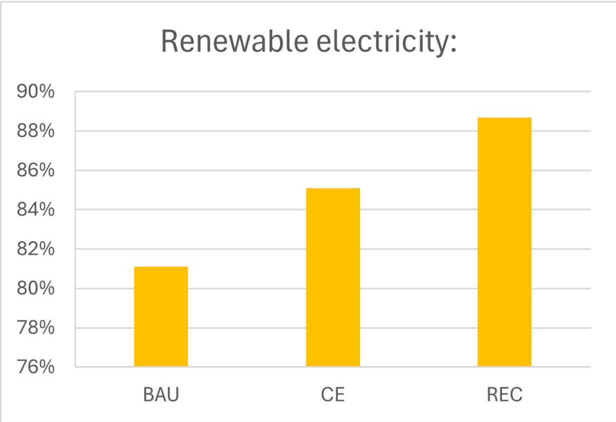
(b) Energy demand.

Figure 6.1: Kicukiro's annual energy demand in 2040.

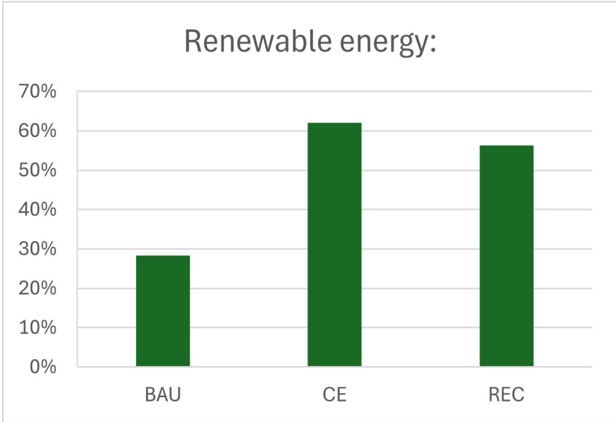
The "Business as Usual" scenario, while it is the one that consumes the lowest amount of electricity, it is the most energy demanding, when buses and cooking are included. The main reason behind this result is its partial reliance on firewood and charcoal for cooking, which is a less efficient method compared to electric, biogas, and LPG stoves. The "Renewable Energy Community scenario", while being the most electricity demanding among the three, due to its higher buildings' consumption and reliance on electric buses, it is the least energy demanding, considering the whole system. The reason behind this is the improved energy efficiency in the cooking and public transport sectors due to adoption of a higher share of LPG stoves, electric buses, and electric stoves, which have a better energy performance compared to their counterparts.

KPI 1.2 - Share of Renewables

The share of renewables, as was done for KPI 1.1, has been divided between electricity and the whole energy system. The results are summarized in the following graphs. It is important to clarify that Firewood and Charcoal used for cooking have not been classified as renewable.



(a) Electricity renewable share.



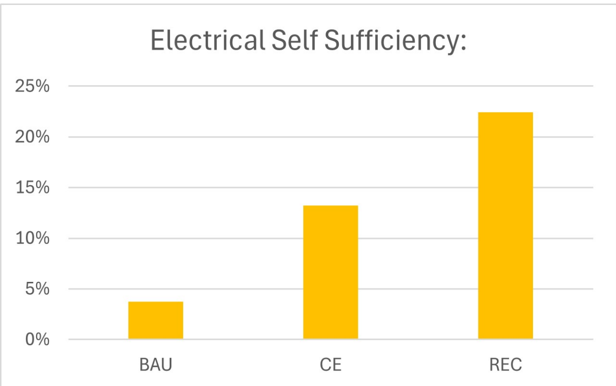
(b) System's renewable share.

Figure 6.2: Kicukiro's energy renewable share in 2040.

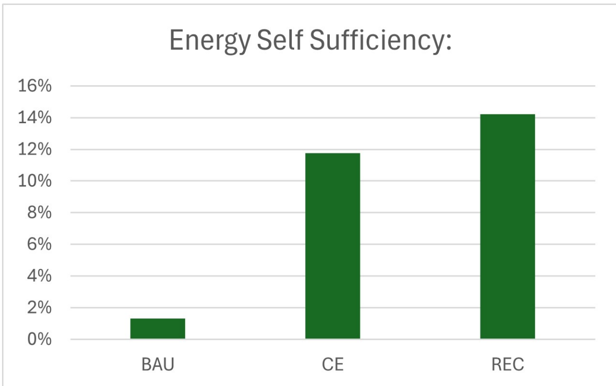
The share of renewable electricity appears to be proportional to the installed PV capacity in each scenario, with the "Renewable Energy Community" scenario being the highest. It is noticeable how the share of renewable electricity is relatively high for each scenario, due to the high renewable fraction of the national grid. Regarding the total share of renewable energy, the "Circular Economy" scenario holds the highest fraction. One of the reasons behind this is its lower reliance on LPG stoves, compared to BAU and REC, due to the adoption of biogas stoves. The REC scenario has the second highest overall renewable share, due to its high renewable electricity fraction and its high reliance on electric buses.

KPI 1.3 - Self Sufficiency

Lastly, the self-sufficiency of Kicukiro has been calculated. The results are reported in the following graphs.



(a) Electrical Self Sufficiency.



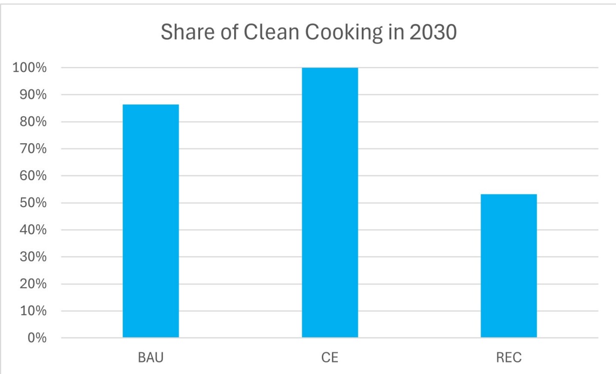
(b) System's Self Sufficiency.

Figure 6.3: Kicukiro's Self Sufficiency in 2040.

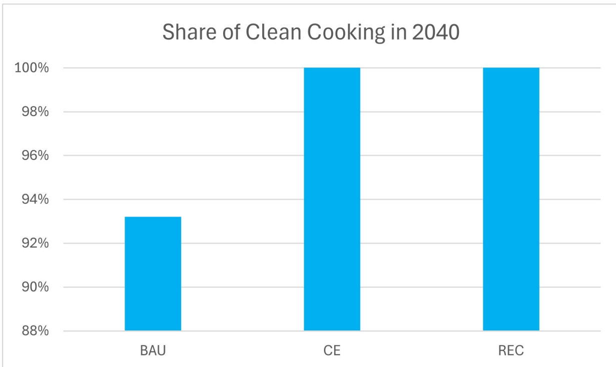
As was the case for KPI 1.2, the "Renewable Energy Community" scenario has the highest electrical self-sufficiency. The additional photovoltaic field and the introduction of energy storage have enhanced the exploiting of the district's solar resource. However, it is noticeable how each scenario remains heavily grid-dependent for their supply of electricity. The results for the whole energy systems indicate a smaller gap between the REC and CE scenarios. The reason behind this is the construction of the biogas digester, which enables the ”Circular Economy” scenario to partially supply its bus fleet by exploiting its waste collection, making the biogas buses totally self-sufficient. The BAU scenario lags behind the others; the main reason is its lower adoption of PV panels, making the system heavily reliant on external resources.

6.1.2 KPI 2 - Share of Clean Cooking

Based on documented projections on universal access to clean modern energy in Kigali [26], the BAU scenario shows steady but incomplete growth in the share of clean cooking access. By 2030, the access rate reaches nearly 90% due to the expected large-scale deployment of LPG (86.4%), gradually improving to 93.2% by 2040. This partial achievement is explained by the continued reliance on traditional biofuels, such as firewood and charcoal. In contrast, the CE scenario achieves universal clean cooking access (100%) already by 2030, as this scenario proposes the complete replacement of traditional biofuels with imported biogas, a complementary alternative to LPG. The REC scenario, while initially slower, reaching only 53.2% access in 2030, achieves universal clean cooking access by 2040, as it considers a conservative yet growing adoption of electric stoves as a clean and non-fossil alternative to traditional biofuels.



(a) Share of household with access to clean cooking in 2030.



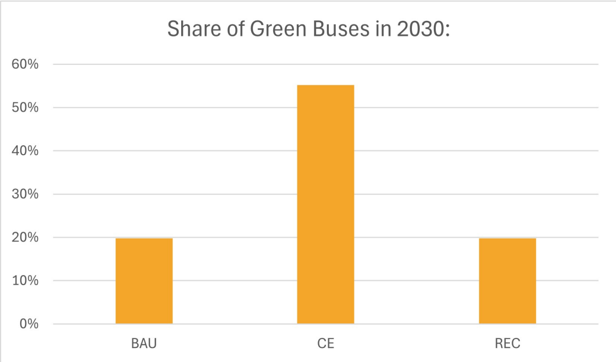
(b) Share of household with access to clean cooking in 2040.

Figure 6.4: Share of household with access to clean cooking in Kicukiro.

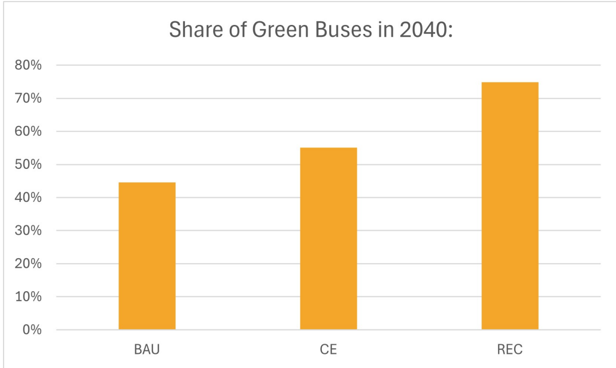
Although the REC scenario is less effective in the short term, its long-term performance aligns with the outcomes of the CE scenario, proving that community-based renewable systems are solid and future-proof solutions to achieve universal clean cooking access.

6.1.3 KPI 3 - Share of Green Buses

Based on the documented goals for 2030, both BAU and REC scenarios, achieve the 20% share by this year. This does not show a high rate of growth, especially for the REC scenario. In contrast, the CE scenario achieves a green bus share of over 55%. This is attributed to the integration of locally produced biogas and conversion into CNG, used as a transport fuel. By 2040 the BAU scenario reaches a green bus share of 45%, which continues the electrification goals from the national strategies aforementioned. The CE scenario maintains its 55% share, which shows the reliance on CNG-fuelled buses. Finally, the REC scenario stands out by achieving a green bus increase of over 75%, reflecting the expansion of electric public transport by 2050. Although the CE scenario leads in 2030, the REC scenario demonstrates stronger potential for the future, supported by electrification and renewable energy development. This highlights the viability of community renewable energy initiatives to transform the transport sector and meet sustainability targets.
Although the CE scenario leads in 2030, the REC scenario demonstrates stronger potential for the future, supported by electrification and renewable energy development. This highlights the viability of community renewable energy in order to transform the transport sector and meet sustainability targets.



(a) Share of green buses in 2030.



(b) Share of green buses in 2040.

Figure 6.5: Share of green buses in Kicukiro's fleet.

6.1.4 Summary tables

Nearly Zero Energy (KPI 1)

Table 6.1: Nearly Zero Energy KPIs for 2040 for each scenario.

Scenario	Electricity	Energy	Unit
KPI 1.1			
BAU	274 144 568.70	786 627 484.99	kWh/yr
CE	286 976 631.00	575 401 260.83	kWh/yr
REC	325 688 970.00	513 600 391.39	kWh/yr
KPI 1.2			
BAU	81.11	28.27	%
CE	85.09	62.09	%
REC	88.67	56.23	%
KPI 1.3			
BAU	3.75	1.31	%
CE	13.25	11.77	%
REC	22.41	14.21	%

Clean Cooking (KPI 2)

Table 6.2: Clean Cooking KPI for each scenario in 2030 and 2040.

Scenario	KPI 2	Unit
2030		
BAU	86.4	%
CE	100	%
REC	53.2	%
2040		
BAU	93.2	%
CE	100	%
REC	100	%

Green Buses (KPI 3)

Table 6.3: Green Buses for each scenario in 2030 and 2040.

Scenario	KPI 3	Unit
2030		
BAU	20	%
CE	55	%
REC	20	%
2040		
BAU	45	%
CE	55	%
REC	75	%

Chapter 7

Economic Assessment

7.1 Pareto frontier

It is inevitable to improve one objective's performance without worsening the performance of another one. A Pareto frontier visualizes the possible trade-offs between competing objectives, making it useful to visualize and identify the best solutions where no objective can be improved and not worsening the other. It helps with the decision-making [55]. The orange dots in each figure below show the more efficient solutions, while the yellow dot the most efficient solution. In this study in particular, the frontiers highlight the trade-off's between economic viability, renewable energy integration and self-sufficiency. The Pareto analysis has been conducted on the "Renewable Energy Community" scenario.

Figure 6.1 compares NPC and self-sufficiency in the system. Due to the complexity of the analysis of the entire system, the evaluation of the Pareto frontiers has been conducted including only the electrical sector. The lowest NPC value is found when 22% of self-sufficiency is obtained. At this point, the balance is optimal between autonomy and cost, and by further increasing the self-sufficiency, it would result in higher cost due to over-dimensioning which would lead to diminishing returns. However, the costs reduces before 22% self-sufficiency is achieved, which could be due to the renewables and the storage being efficiently integrated. This frontier amplifies the importance of aiming for an autonomy range that is optimal for the system, rather than striving for the highest value of self-sufficiency. In 6.2, the frontier visualizes that the NPC changes depending on the amount of energy that comes from renewables. The most economical solution is found when approximately 88.7% of the energy is obtained from renewable sources. The cost decreases as the share of renewables increases up to that point. With this frontier it is shown that a high share of renewables is besides environmentally friendly, also more affordable. Lastly, figure 6.3 shows how self-sufficiency affects the net renewable energy fraction (NRF). There is an improvement up until 89.6% of NRF is achieved. Beyond this point, the additional renewables results in a small difference in self-sufficiency. This Pareto frontier, like 6.1, visualizes that rather than aiming for a maximal number in self-sufficiency, it is better to aim for the combination that results in a well balanced system.

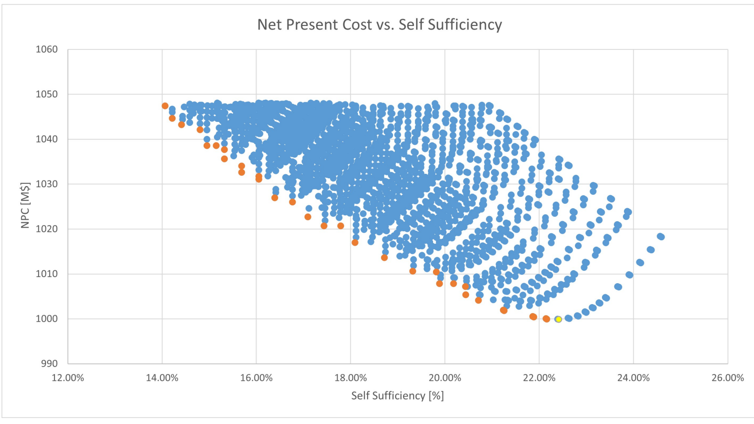


Figure 7.1: Pareto frontier 1. Net present cost vs. Self sufficiency.

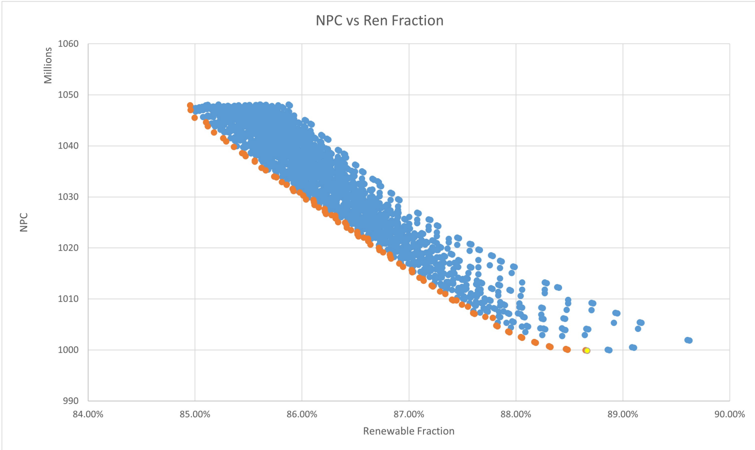


Figure 7.2: Pareto frontier 2. Net present cost vs. Renewable fraction.

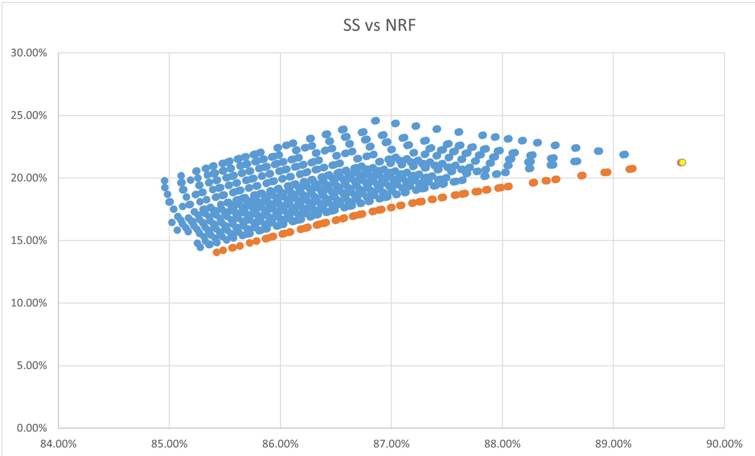


Figure 7.3: Pareto frontier 3. Self sufficiency NRF.

7.2 Financial analysis

7.2.1 General description

The analysis was performed on the Solar PV panels, the cooking technologies, the buses used in transport and the biodigesters. The following calculations uses the nominal discount rate of 8% and an inflation rate of 5%.

Four different formulas were used in the economic assessment to evaluate different economic aspects for each scenario. The indicators that were used are Net Present Value (NPV), Discounted Payback period (T_{dp}), Benefit to Cost ratio and lastly, Internal Rate of Return (IRR). The table below shows the definition of each variable that was used.

Symbol	Description
C	Annual cost
C_0	Initial cost
B	Annual benefit
i	Real discount rate
n	Lifetime

The Capital Investment Costs (CAPEX) is equivalent to C_0 and the Operational and Maintenance costs (OPEX) are equivalent to C in the used formulas.

7.2.2 Assumptions made

The Annual benefit is defined differently for every component. For each of them, the benefit was quantified by evaluating the effect of adopting the respective technologies. Since there was no net positive cash flow, expenditures that have been avoided, due to technological replacement, were considered as such. For buses used in transport, it was considered to be the price of diesel multiplied by the total consumption. Regarding the biogas-fuelled buses, since the fleet consumes locally-produced fuel, the OPEX is already included in the biodigester's costs. The benefit relative to the purchased stoves (LPG, biogas and electric) is quantified by the avoided cost of using charcoal and firewood for cooking. The simplified formulas can be seen below.

$$B_{\text{LPG/biogas stoves}} = C_{\text{Charcoal}} \times \text{Consumption} \tag{7.1}$$

$$B_{\text{electrical stoves}} = C_{\text{Charcoal}} \times \text{Consumption} \tag{7.2}$$

$$B_{\text{transport}} = C_{\text{Diesel}} \times \text{Consumption} \tag{7.3}$$

7.2.3 Indicators used

The NPV considers the cash flows over the economic life of the investment and gives the total current value of the investment. All the NPV values calculated were added to each other. A feasible measurement translates into a positive NPV value, because it is directly proportional to the benefit. Although, this value does not indicate the size of the initial investment costs [55].

$$\text{NPV} = \sum_{j=1}^{n} \frac{B_j - C_j}{(1+i)^j} - C_0 + \frac{S}{(1+i)^n} \tag{7.4}$$

Equation (7.4) is the general formula, in this case, the salvage value is not considered since it is assumed that all investments are eventually going to be used over their entire lifespan.

The Discounted Payback Period considers the time value of money and indicated how long it takes to pay back for the project. For the project to be feasible, the payback period must be lower than the project's lifetime, otherwise it is not a profitable investment.[55].

$$T_{dp} = \frac{\ln(B - C) - \ln\left((B - C) - i \times C_0\right)}{\ln(1 + i)} \tag{7.5}$$

Since this method of evaluating investments solely deals with constant annuities (both in benefits and costs), and a single upfront investment, it has been used individually for every different PV panel investment scheme. However, it was not possible to implement over the entirety of the investments per scenario.

The saving-to-investment ratio or the also named Benefit-to-cost ratio calculates the present worth of all benefits on the numerator and the present worth of all costs in the denominator. The quota then gives the BCR value [55].

$$\text{BCR or } \frac{\text{B}}{\text{C}} = \frac{\sum_{j=1}^{n} \frac{B_j}{(1+i)^n}}{\left[\sum_{j=1}^{n} \frac{C_j}{(1+i)^n}\right] + C_0} \tag{7.6}$$

The value for Internal Rate of Return (IRR) indicates the value of the discount or interest rate making the present worth of the project's costs equal to the present worth of the project's benefits [55]. A built-in function from Excel was used to calculate this value, with the following command (”=IRR([values];’estimation’”).

7.2.4 Considerations

It is worth considering that these calculations and the whole financial assessment does not account for factors that are beyond the project's control, such as fuel risks, security benefits or climate change [55]. Examples of other aspects that are not accounted for would be battery replacement costs for EV buses, cost of infrastructure such as charging stations or biogas refuelling stations, or servicing and repairs for the buses. For the EV buses particularly, it is worth noting that 'BasiGo' is a bus operating company in Kenya and Rwanda, offering a Pay-as-you-drive subscription for the leasing of its buses. It was considered that the company would maintain its service in the future, allowing not to take into account for the extra infrastructure costs. Additionally, CAPEX has not been considered for the buses, since they are being leased. Lastly, when accounting for the cooking stoves, the replacement throughout the years is not considered. This analysis has been subject to simplifying assumptions, it has to be considered as an initial evaluation that includes the main measures considered, rather than an in-depth, realistic economical evaluation. However, these tools provides a good enough foundation to evaluate the most profitable scenario.

7.2.5 Results

Table 7.1: Financial Analysis results for every scenario.

Scenario	$T_{\text{dp, solar PVs}}$ [yrs]	NPV [M USD]	BTC [ratio]	IRR [%]
BAU	4.0	44.2	1.40	6
CE	4.4	63.4	1.25	10
REC	4.0	273.8	1.78	12

Table 7.1 presents the values yielded by the economical analysis. It can be seen that the BAU and CE Scenarios differ (lower investment in the BAU Scenario yielding a higher BTC), but the higher resulting NPV in the CE Scenario goes with the associated higher IRR. Moreover, it can be seen that from an economical standpoint,

managing to secure enough funds to carry out the REC Scenario would be economically advantageous. Based on the obtained results, it can be observed that the CE and the REC scenario are both profitable based on their respective NPV values. A higher BTC value indicates a more profitable investment, and the best value is obtained from the REC scenario. As for the payback time, it differs from 20% - 22% of the lifetime of the project for all the scenarios, which overall is considered good. In addition, the IRR value is the highest for REC, indicating a solid economic return compared to the other scenarios. To conclude, since the REC scenario has the highest NPV and BTC value, and a payback period (concerning the PVs) that is shorter than the CE scenario, it is the most profitable one from an economical standpoint, hence the recommended one.

7.3 Sensitivity Analysis

A sensitivity analysis was made on the REC scenario to assess how several parameters affect the overall system and cost-effectiveness. The values presented are exclusive of HOMER Pro simulations. Figure 7.4 shows the relationship between the Net Present Cost (NPC) and the discount rate for the entire electrical system. Studying the graph, it is possible to notice that the NPC decreases as the discount rate increases, highlighting the inverse relationship between these two variables.

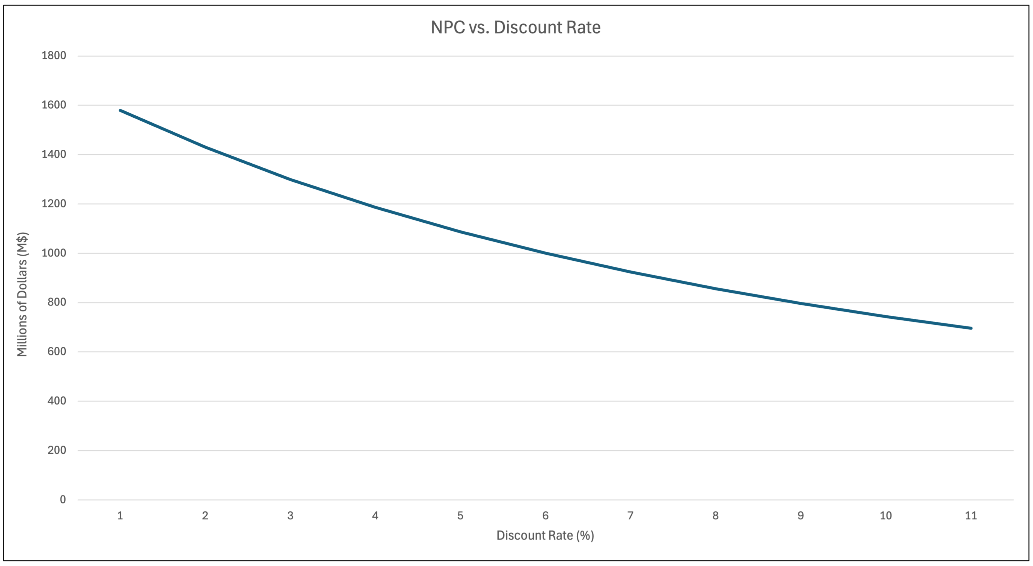


Figure 7.4: Net Present Cost versus Discount Rate Analysis.

Interpreting the results, it is understandable that at lower discount rates, future costs are given more weight in present value, resulting in a higher NPC. As the discount rate increases, the present value of future expenditures tends to decrease, leading to a lower NPC. This trend shows that choosing the discount rate is crucial for the financial evaluation. Therefore, understanding the sensitivity of NPC to changes in the discount rate is essential for assessing the economic feasibility and risks that renewable energy investments might have.

Figure 7.5 presents a sensitivity analysis of the Levelized Cost of Electricity (LCOE) for three key parameters: the capital expenditure of photovoltaic (PV) systems, battery storage systems, and the price of electricity from the grid. Each parameter can be seen in a different colored line.

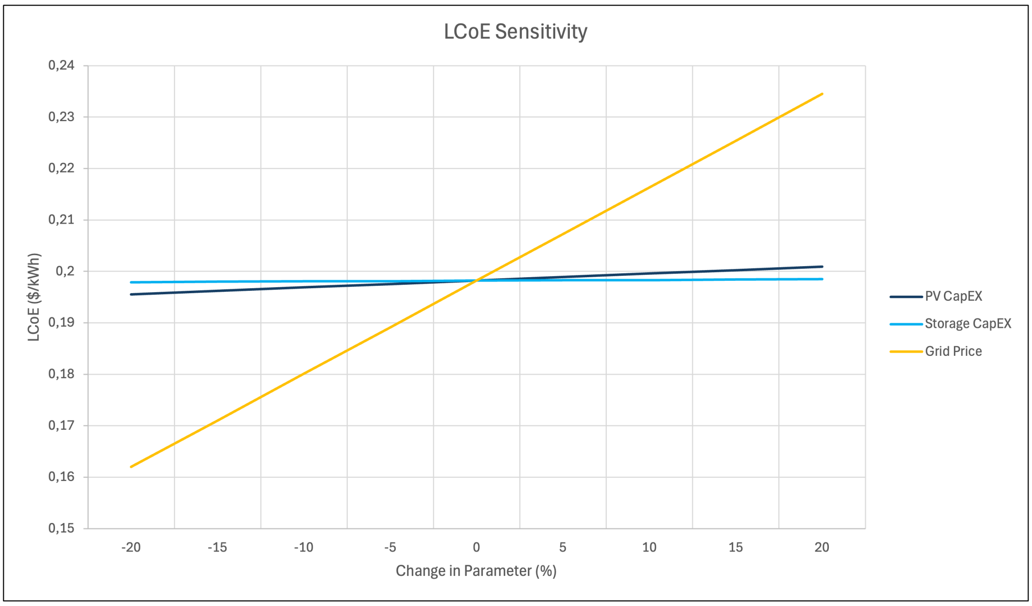


Figure 7.5: Sensitivity Analysis of Levelized Cost of Electricity in PV pannels, batteries and prices of electricity.

The x-axis is the variation in each parameter, from -20% to +20%, while the y-axis shows the corresponding variation in LCoE. The analysis demonstrates that the LCoE is more sensitive to changes in the price of grid electricity. A 20% increase in grid price results in a rise in LCOE, as indicated by the steep slope of the yellow line. Changes in the CAPEX for PV panels and battery storage have less impact on LCOE, which demonstrates that while investments in PV and storage technologies affect the cost of electricity, fluctuations in the grid electricity price are much more impactful. By examining these sensitivities, it is possible to understand the robustness of each scenario and support informed decision-making when planning and optimizing sustainable energy systems.

Chapter 8

Business Model Innovation

The third scenario provides the highest share of renewable energy in terms of solar power, and there are opportunities within the off-grid solar park in the community to generate the adequate funding. For the scenario Renewable Energy Community, TekiniKicukiro recommends *LUMA - Local Utility Membership for All*. It is a categorized membership-based cooperative for solar PV energy in Kicukiro. The name LUMA means ”light” in Latin and the name emphasizes inclusivity.

The model is made for everyone, meaning that citizens, institutions and supporters can contribute together to different extents to consume, generate or support clean energy. The decision-making and the ownership are shared and the cooperative has its voting members, being the generating and consuming members. In addition, there are supporters and partners that provide guidance and funding. One of the key partners, seen in the business model canvas below, is the City of Kigali who backs up and supports the model with land and policies. The proposal is defined in accordance to the law Nº 024/2021 governing cooperatives in Rwanda [56]. The law defines membership rights, legal registration, financial reporting and governance. To ensure donor compatibility, the proposal is also aligned with the RED II - EU Renewable Energy Directive. Its framework is recognized among climate finance institutions in the EU and enhances donor compatibility with climate finance mechanisms and EU-aligned institutions [57].

The generating members are the ones who install or invest in solar and help produce electricity. The consuming members, being any PV consumer but mostly households, then access the affordable clean energy. Donors such as non-governmental organizations (NGO:s) fund the system and do not influence the governance. The investments from the donors help this model, and thereby help Kicukiro to achieve the seventh sustainable development goal (SDG7), which includes increased access to electricity and renewable sources [58].

The revenue streams are the entry and monthly fees, surplus energy sales, grants and donations. However, the streams differ depending on the class. The consumer and the generators pay an one-time entry fee, standing at 25% of the monthly salary, to get the voting rights and to be a part of the shared ownership. Thereafter, for the consumers, there is a monthly subscription payment of 10% to every electricity bill to get continued access to the co-op services. There are solar projects in Maine (USA), Kenya and Rwanda with different fees and revenue streams. To find a reasonable fraction, already existing projects within the field were benchmarked [59][60][61].

Prices could be adapted if it is requested by the voting members. If necessary, a willingness-to-pay survey could be completed to adapt the fractions based on the district's requests. A fixed price was not selected to ensure that a higher number of lower-income households can participate in the cooperative. A higher participation rate can be achieved if prices are tailored to each specific income and electricity bill.

For the generating members, the produced electricity is partially consumed for internal usage, and the surplus is sold to be used to the consumers in the model. The electricity bill paid by the consumers is directed to the generator, but the additional 10% is for the co-op to keep the system going and gain funding. Since there are no transmission costs within this system, the energy price is overall lower for the consumers, which makes this cooperative an economically more feasible alternative to electricity access. Additionally, the reduced dependency on the grid ensures stronger energy security. The flow chart below visualizes the streams.

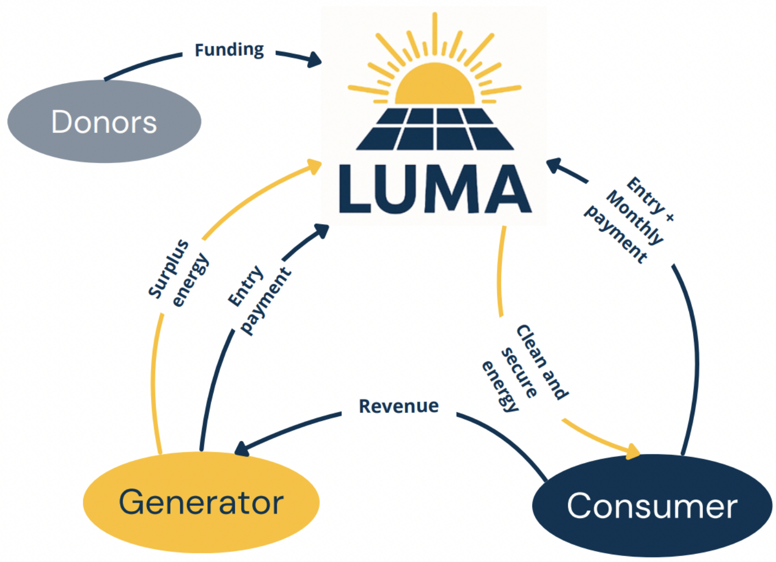


Figure 8.1: Business Model Flowchart.

Each member in this model can contribute differently, either through usage or capital investment and, in return, they share the benefits of receiving better energy security and long-term sustainability. A synergy with the model is the potential job opportunities that could be created due to the technical staff needed for maintenance. The business model canvas below provides a simplified and concrete overlook into the components within the cooperative model.

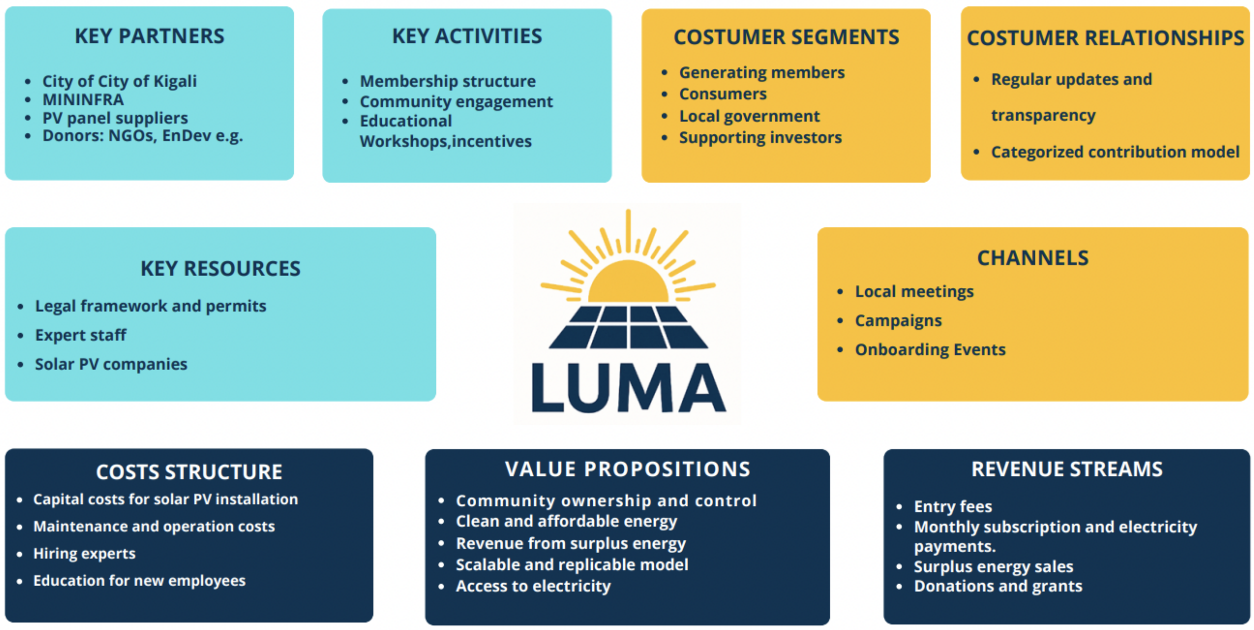


Figure 8.2: Business Model Canvas.

Chapter 9

Conclusions and Final Recommendation

This project explored how Kicukiro's district could be energetically enhanced through the projection of different scenarios, in order to transition into a sustainable future. The scenario that demonstrated the ability to cover these features while aligning with the goals projected not only by Rwanda's Government and Ministry, but also made along this project, was the REC scenario. It proposes full electrification, which determines modifications in the transport, cooking, and building sectors, through the implementation of solar PVs and storage. This results in the highest renewable and self-sufficiency share obtained throughout the project, reducing emissions, aiming to be carbon neutral, and accessible to every citizen, according to the LUMA business model. However, this scenario comes with high investment costs, which are understandable given its complexity and components. The needed investment will be returned in the future, as this is a scenario that is tailored to be reliable long-term.

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Chapter 10

Appendix

10.1 Biodigester

Table 10.1: Explanation of terms used for biodigester volume calculation.

Term	Meaning	Unit
$w_{capita,day}$	Waste produced per person every day	$\frac{kg}{day}$
P_{tot}	Total population	-
$S_{collected}$	Share of collected waste	$\%$
TS	Total solids fraction	$\%$
VS	Volatile solids fraction	$\%$
Y	Biogas Yield	$\frac{m^3}{kg_{VS}}$
V_{bio}	Volume of produced biogas	$\frac{m^3}{day}$
ρ_{bio}	Density of biogas (60% CH4, 40% CO2)	$\frac{kg}{m^3}$
HRT	Hydraulic Retention Time	Days
V_{needed}	Biodigester volume needed	m^3
S_{bio}	Share of biowaste	$\%$

$$V_{bio} = w_{capita,day} \cdot S_{bio} \cdot P_{tot} \cdot S_{collected} \cdot TS \cdot VS \cdot Y \tag{10.1}$$

The ratio between the substrate (the biowaste input to the biodigester) and water is 1:1. This implies a multiplication factor of 2 (assuming that head space is not required).

$$V_{needed} = \frac{w_{capita,day} \cdot S_{bio} \cdot P_{tot} \cdot S_{collected} \cdot 2 \cdot HRT}{1000} \tag{10.2}$$

10.2 Public Transport Sector

This table shows the consumption found and mentioned in Section 5.2 for diesel buses:

Table 10.2: Consumption of Diesel Buses converted into L/km

	Medium buses (7m)	Large buses (12m)
	Toyota Coaster	Benz Citaro
Consumption (L/100km)	12,5	46,1
Consumption (L/km)	0,125	0,461

In the following table, the number of large and medium buses is shown for the year 2040, which was crucial for the comparison of yearly consumption throughout this section. Their yearly consumptions was also calculated, as shown also in section 5.2

Table 10.3: Calculation of Yearly demand of Diesel bus (sorted)

Scenario 1	2040	Yearly consumption (kWh/year)	share %
# Large buses diesel:	86	23751508,45	0,34817814
#Medium buses diesel:	51	3819196,549	0,20647773
Total		27570705	
Scenario 2			
# Large buses diesel:	60	16570819,85	0,24291498
#Medium buses diesel:	51	3819196,549	0,20647773
Total		20 390 016,40	
Scenario 3			
# Large buses diesel:	11	3037983,639	0,04453441
#Medium buses diesel:	51	3819196,549	0,20647773
Total		6857180,189	

As stated in Section 5.2 the amount of buses was projected based on the yearly growth of population. This was achieved by

$$\text{Total Buses} = \text{Total Buses (Row before)*(1+\%increase)} \tag{10.3}$$

The results are stated in the table below:

Table 10.4: Bus number projections from 2023 until 2050, Scenario BAU (1) and Scenario REC (3)

Population			Business as usual			Scenario 3	
Year	% Increase	Total	Total buses	Total diesel-buses	Number of total EV-buses	Number of total diesel buses	Number of total EV-buses
2023	0,04489528	510 900	-	-	-	-	-
2024	0,04408836	533 837	-	-	-	-	-
2025	0,0432242	557 373	140	140	-	-	-
2026	0,0432242	581 465	146	146	-	-	-
2027	0,04252707	606 193	152	152	-	-	-
2028	0,04202127	631 666	159	158	-	-	-
2029	0,04140321	657 819	165	165	-	-	-
2030	0,04056891	684 506	172	138	34	138	34
2031	0,0397323	711 703	179	138	41	130	49
2032	0,03908231	739 518	186	138	48	122	64
2033	0,0386749	768118,785	193	138	55	114	79
2034	0,03805639	797350,612	200	138	63	106	94
2035	0,03743788	827201,727	208	138	70	98	110
2036	0,03681937	857658,771	215	138	78	91	125
2037	0,03620086	888706,753	223	138	86	84	140
2038	0,03558235	920329,023	231	138	94	76	155
2039	0,03496383	952507,254	239	138	102	69	170
2040	0,03434532	985221,423	247	138	110	62	185
2041	0,03372681	1018449,8	256	138	118	56	200
2042	0,0331083	1052168,94	264	138	127	49	215
2043	0,03248979	1086353,69	273	138	135	43	230
2044	0,03187128	1120977,17	282	138	144	36	245
2045	0,03125277	1156010,81	290	138	153	30	261
2046	0,03063426	1191424,34	299	138	162	24	276
2047	0,03001575	1227185,83	308	138	171	18	291
2048	0,02939723	1263261,7	317	138	180	12	306
2049	0,02877872	1299616,76	326	138	189	6	321
2050	0,02816021	1336214,24	336	138	198	0	336

For the share of biogas used, the logic is explained in section 5.2, thus the full table is shown below:

Table 10.5: overall consumption calculation of biogas

	Share biogas buses	Biogas Buses	Biogas(kg/day)	Biogas(m3/day)	Biogas needed (m3/year)
2030	55%	95	7754,18	9415,79064	3 436 763,58
2040	55%	136	11160,73	13552,3117	4 946 593,76

10.3 Cooking Sector

In this section the calculations performed to obtain the total energy demand of the cooking sector are shown for every fuel.

Table 10.6: Explanation of terms used for Firewood and Charcoal calculations.

Term	Meaning	Unit
$E_{\text{F\&C}}$	Yearly energy needed for Firewood and Charcoal cooking	$\frac{\text{TJ}}{\text{yr}}$
$\%_{\text{HH,F\&C}}$	Share of households that use Firewood and Charcoal	%
$m_{\text{F\&C,CS}}$	Amount of Firewood and Charcoal used per cooking session	$\frac{\text{kg}}{\text{HH*CS}}$
n^o_{CS}	Number of cooking sessions per day	–
n^o_{days}	Number of days per year	$\frac{\text{days}}{\text{year}}$
$\text{LHV}_{\text{F\&C}}$	Lower heating value of Firewood and Charcoal	$\frac{\text{kJ}}{\text{kg}}$

$$E_{F\&C} = \frac{n^{\circ}_{\text{HH},F\&C} \cdot \%\_\text{HH}, F\&C \cdot m_{F\&C,\text{CS}} \cdot n^{\circ}_{\text{CS}} \cdot n^{\circ}_{\text{days}} \cdot \text{LHV}_{F\&C}}{1\,000\,000} \tag{10.4}$$

10.3.1 LPG

Table 10.7: Explanation of terms used for LPG calculations.

Term	Meaning	Unit
E_{LPG}	Yearly energy needed for LPG stoves	$\frac{\text{TJ}}{\text{yr}}$
$\%_{\text{HH,LPG}}$	Share of households with an LPG stove	%
$m_{\text{LPG,capita,month}}$	Amount of LPG used per person per month	$\frac{\text{kg}}{\text{capita}}$
n^o_{HH}	Total number of households	–
$n^o_{\text{people,HH}}$	Number of people per household	–
n^o_{months}	Number of months per year	$\frac{\text{months}}{\text{year}}$
LHV_{LPG}	Lower heating value of LPG	$\frac{\text{kJ}}{\text{kg}}$

$$E_{\text{LPG}} = \frac{n^{\circ}_{\text{HH}} \cdot \%_{\text{HH,LPG}} \cdot m_{LPG,capita,month} \cdot n^{\circ}_{\text{months}} \cdot n^{\circ}_{\text{people,HH}} \cdot \text{LHV}_{\text{LPG}}}{1\,000\,000} \tag{10.5}$$

10.3.2 Biogas

Table 10.8: Explanation of terms used for Biogas calculations.

Term	Meaning	Unit
E_{Biogas}	Yearly energy needed for Biogas stoves	$\frac{\text{TJ}}{\text{yr}}$
$\%_{\text{HH,Biogas}}$	Share of households with a Biogas stove	$\%$
h_{session}	Amount of hours needed for every cooking session	h
n^{o}_{session}	Number of cooking session	–
C_{Stove}	Consumption of a Biogas stove	$\frac{m^3}{\text{h}}$
ρ_{biogas}	Biogas density	$\frac{\text{kg}}{m3}$
$\text{LHV}_{\text{Biogas}}$	Lower heating value of Biogas	$\frac{\text{kJ}}{\text{kg}}$

$$E_{\text{Biogas}} = \frac{n^{\circ}_{\text{HH}} \cdot \%_{\text{HH,Biogas}} \cdot h_{session} \cdot n^{\circ}_{\text{session}} \cdot C_{\text{Stove}} \cdot \rho_{Biogas} \cdot \text{LHV}_{\text{Biogas}}}{1\,000\,000} \tag{10.6}$$

10.3.3 Electricity

Table 10.9: Explanation of terms used for electricity calculations.

Term	Meaning	Unit
$E_{\text{Electricity}}$	Yearly energy needed for electricity stoves	$\frac{\text{TJ}}{\text{yr}}$
$\%_{\text{HH,Electricity}}$	Share of households with an electric stove	$\%$
$C_{\text{Electric,day}}$	Consumption of an electric stove in a day	$\frac{\text{MJ}}{\text{day}}$
$n^{\circ}_{\text{day,year}}$	Number of days in one year	–

$$E_{\text{Electricity}} = \frac{n^{\circ}_{\text{HH}} \cdot \%_{\text{HH,Electricity}} \cdot C_{Electric,day} \cdot n^{\circ}_{\text{day,year}}}{1\,000\,000} \tag{10.7}$$

10.4 HOMER Pro

10.4.1 PV costs calculations

CAPEX

The Capex and Opex costs for the PV panels have been calculated following this procedure. The capital cost of utility-scale South African PV panels for 2023 has been taken as a reference [49]. The price has been then projected to 2030, according to the NREL's "moderate" scenario for the PVs installed in the USA [50].

The estimation is based on a simple proportion; an example for the capital cost of utility-scale PVs is provided below:

$$C_{USA,2023} = 1610 \text{ USD/kW}$$

$$C_{S.A./Rwanda,2023} = 1255 \text{ USD/kW}$$

$$C_{USA,2030} = 1193 \text{ USD/kW}$$

$$C_{S.A./Rwanda,2030} = \frac{C_{S.A./Rwanda,2023} \cdot C_{USA,2030}}{C_{USA,2023}} = 930 \text{ USD/kW}$$

Table 10.10: Capex costs for South African/Rwandan PVs and US PVs for 2023 and 2030.

YEAR	**2023**	**2030**
USA Utility-Scale PV cost [USD/kW]	1610.00	1193.00
S.A./Rwanda Utility-Scale PV cost [USD/kW]	1255.00	**930.00**
USA Commercial PV cost [USD/kW]	1845.00	1310.00
S.A./Rwanda Commercial PV cost [USD/kW]	1438.00	**1021.00**
USA Residential PV cost [USD/kW]	2682.00	2110.00
S.A./Rwanda Residential PV cost [USD/kW]	209.001	**1644.75**

OPEX

The evaluation of Opex costs is based on the same NREL estimation for 2030, which defines the yearly Opex as a percentage of the Capex for PVs installed in the US. It has been assumed that the proportion is the same for the Rwandan case and remains constant for the following years.

Table 10.11: Opex cost for S.A./Rwandan PVs.

YEAR	**2030**
Utility-Scale PV Opex [% of Capex]	**1.5**
Commercial PV Opex [% of Capex]	**1.06**
Residential PV Opex [% of Capex]	**1.16**

10.4.2 Search Spaces

Business as Usual

Table 10.12: Search spaces for PVs in ”Business as Usual”.

RESIDENTIAL PV [kW]
0
1000
2000
2964

COMMERCIAL PV [kW]
0
1000
2000
3000
4000
4781

Circular Economy

Table 10.13: Search spaces for PVs in "Circular Economy".

RESIDENTIAL PV [kW]
0
2000
3000
5000
7000
9000
11000
14000
16000
16077

COMMERCIAL PV [kW]
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14834

Renewable Energy Community

Table 10.14: Search spaces for PVs in "Renewable Energy Community".

RESIDENTIAL PV [kW]
0
2000
3000
5000
7000
9000
11000
14000
16000
16077

COMMERCIAL PV [kW]
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15936

PV FIELD [kW]
0
5189
13405
22054
27460

Table 10.15: Search space for batteries in "Renewable Energy Community".

OF 1MWh BATTERIES
0
10
20
30
40
50
60
70
80
90
100

10.4.3 Final layouts

Business as Usual

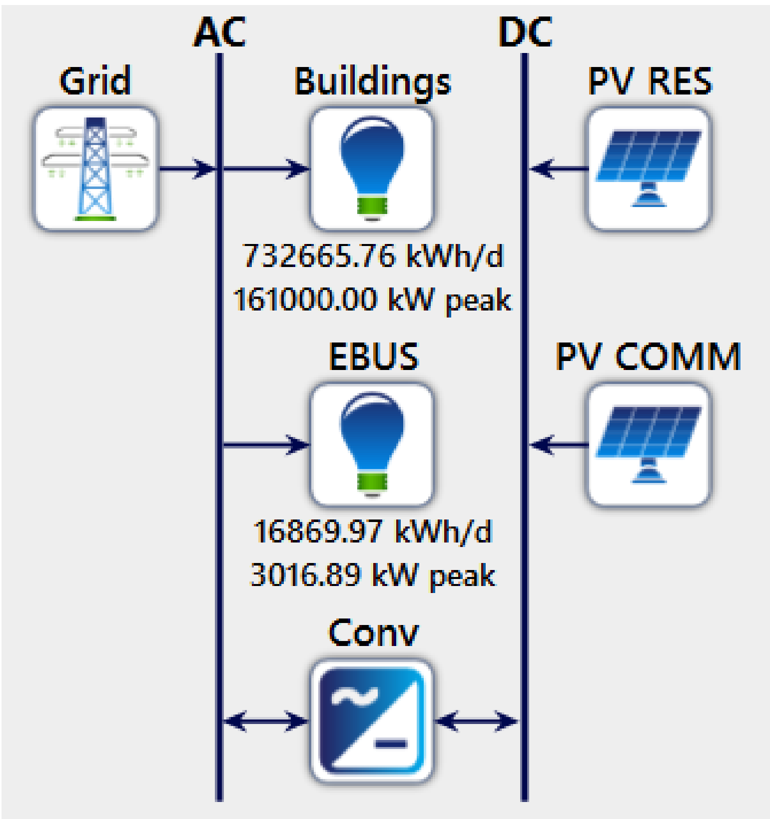

Figure 10.1: System layout for "Business as Usual".

Circular Economy

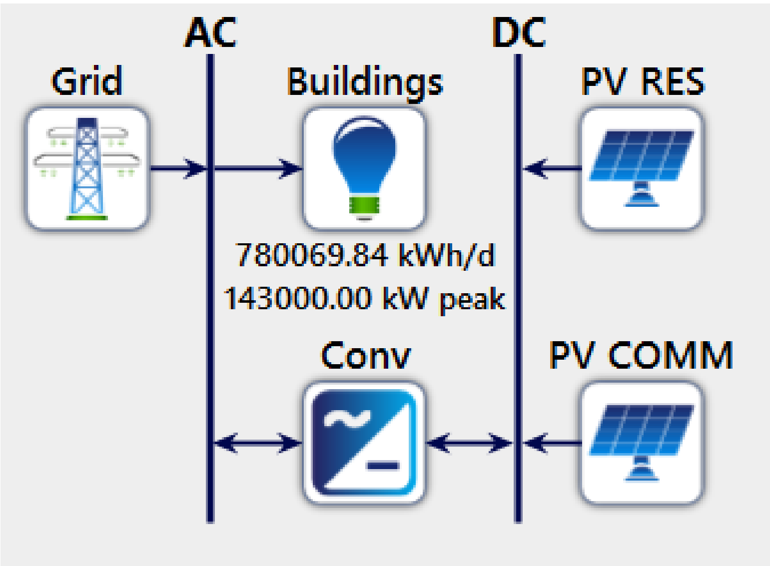

Figure 10.2: System layout for "Circular Economy".

Renewable Energy Community

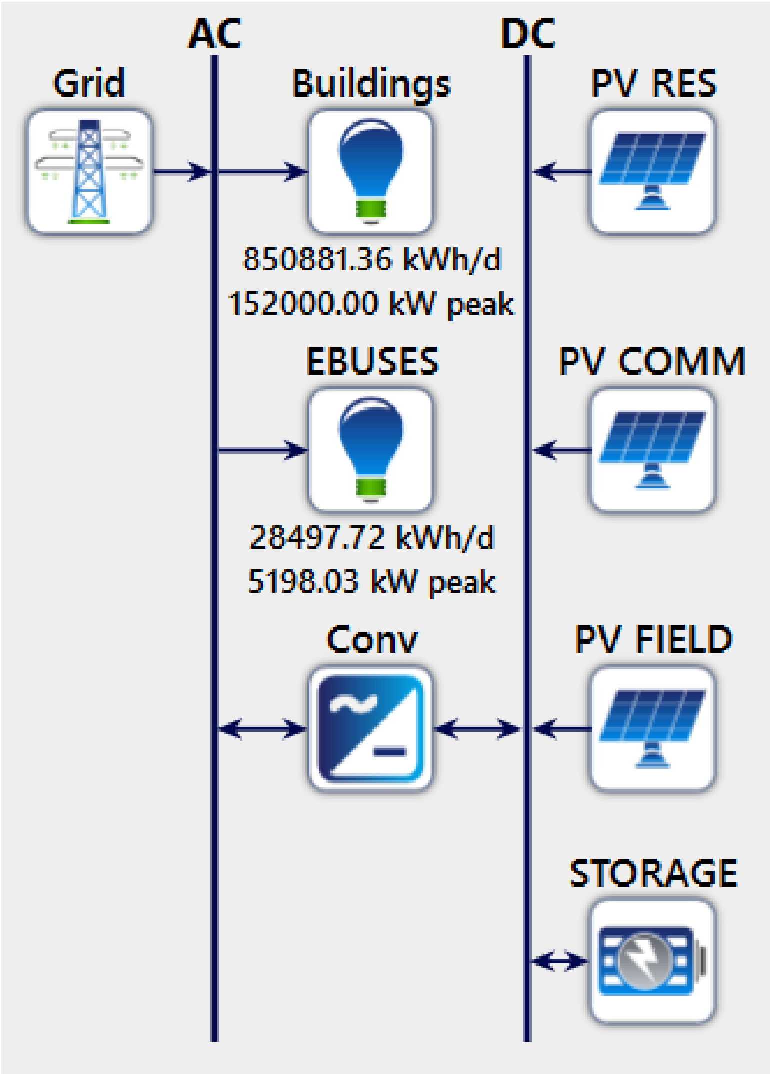

Figure 10.3: System layout for "Renewable Energy Community".

10.5 ArcGIS Pro

10.5.1 Building archetypes description

The following section presents descriptions of the various building archetypes, based on the classification proposed by Bachofer et al. (2019) [47] and the data extracted from the provided shapefile for Kicukiro district in 2015.

Basic buildings

Basic buildings are the predominant building archetype in Kigali and Kicukiro. They are low-rise buildings with just one floor present in both densely built-up and rural areas.

Table 10.16: Basic building archetype characteristics in Kicukiro.

Code	Name	Building Average Height in Kicukiro (m)	Building Average Floor Area in Kicukiro (m^2)
1	Basic	2.4	65.2

Block buildings

Block buildings consist of highly dense building settlements around the perimeters of a block. With one to three floors, this archetype can be considered to have a higher quality than the Basic archetype, and they are mostly found around areas with high traffic.

Table 10.17: Block building archetype characteristics in Kicukiro.

Code	Name	Building Average Height in Kicukiro (m)	Building Average Floor Area in Kicukiro (m^2)
2	Block	2.7	141.0

Bungalow buildings

Bungalow archetypes follow semi-detached or detached patterns, with a higher quality construction than Basic and Block archetypes.

Table 10.18: Bungalow building archetype characteristics in Kicukiro.

Code	Name	Building Average Height in Kicukiro (m)	Building Average Floor Area in Kicukiro (m^2)
3	Bungalow	3.6	176.7

Villa buildings

Villa buildings are detached and high quality archetypes, surrounded by large outdoor spaces. Construction material qualities can be a key factor when distinguishing between Bungalows and Villas.

Table 10.19: Villa building archetype characteristics in Kicukiro.

Code	Name	Building Average Height in Kicukiro (m)	Building Average Floor Area in Kicukiro (m^2)
4	Villa	4.5	270.3

Mid-rise buildings

Low to mid-rise buildings are multi-storey dwellings in which different family units live. They have between one to four floors and most often are detached buildings.

Table 10.20: Mid-rise building archetype characteristics in Kicukiro.

Code	Name	Building Average Height in Kicukiro (m)	Building Average Floor Area in Kicukiro (m^2)
5	Mid-rise	5.1	619.0

High-rise buildings

High-rise buildings have a higher height than Mid-rise archetypes. They are multifamily units dwellings, mostly present in newly-built areas.

Table 10.21: High-rise building archetype characteristics in Kicukiro.

Code	Name	Building Average Height in Kicukiro (m)	Building Average Floor Area in Kicukiro (m^2)
6	High-rise	11.9	711.5

Hall buildings

Hall buildings are primarily identified due to their large floor area, with more than 100 m^2, and their rectangular shape.

Table 10.22: Hall building archetype characteristics in Kicukiro.

Code	Name	Building Average Height in Kicukiro (m)	Building Average Floor Area in Kicukiro (m^2)
7	Hall	3.8	566.8

Special structures

This archetype refers to certain structures that do not fall behind any other archetype, such as energy or telecommunications infrastructures.

Table 10.23: Special structure archetype characteristics in Kicukiro.

Code	Name	Building Average Height in Kicukiro (m)	Building Average Floor Area in Kicukiro (m^2)
8	Special	2.6	161.7

Construction sites

This archetype is assigned to those areas in which no other building type can be assigned and construction activity is identified.

Table 10.24: Construction site archetype characteristics in Kicukiro.

Code	Name	Building Average Height in Kicukiro (m)	Building Average Floor Area in Kicukiro (m^2)
9	Construction	2.4	267.5

10.5.2 Building archetypes distribution

The distribution of the different building archetypes is presented below. This classification allowed the identification of the most relevant archetypes for consideration in the building energy modelling of this project.

Table 10.25: Building archetypes distribution and characteristics in Kicukiro.

Archetype	1	2	3	4	5	6	7	8	9
Number of Buildings (2015)	46 082	315	11 278	2 087	184	25	1 726	58	393
Building Average Height (m)	2.4	2.7	3.6	4.5	5.1	11.9	3.8	2.6	2.4
Building Average Floor Area (m^2)	65.2	141.0	176.7	270.3	619.0	711.5	566.8	161.7	267.5

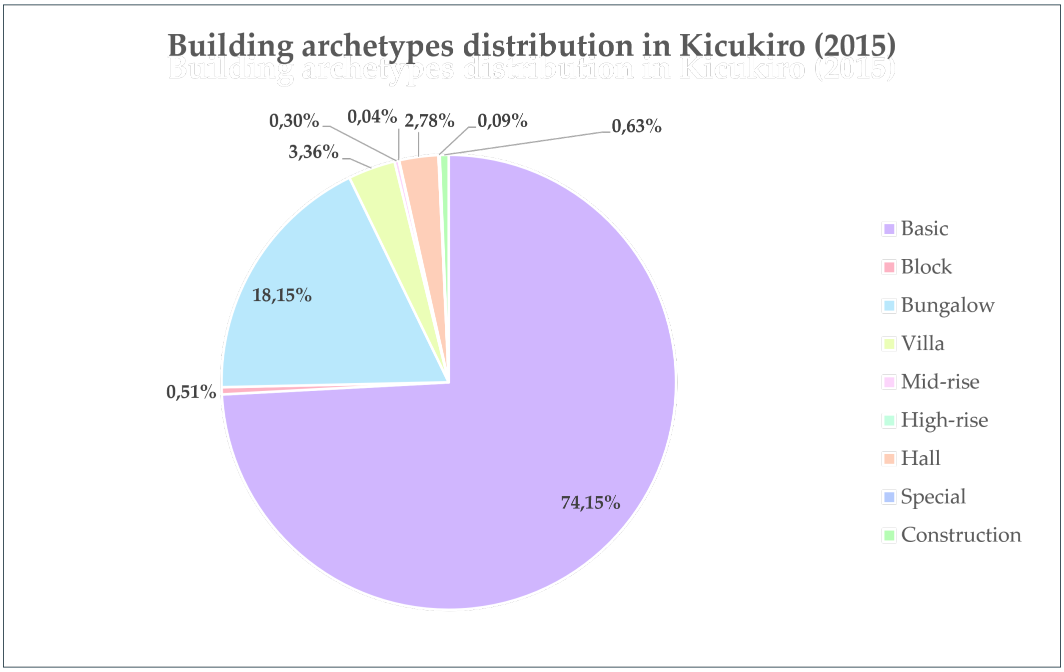

Figure 10.4: Building archetypes distribution in Kicukiro for 2015.

10.6 IDA ICE

10.6.1 Building archetypes modelling

The following section details the parameters and construction characteristics for each building archetype modelled in IDA ICE. Lastly, the results of the simulation conducted in IDA ICE are presented.

Basic buildings

Table 10.26: Elements of construction U-values (W/m^2·K) used in IDA ICE to model the Basic building archetype.

Archetype	1 Basic
External Walls (W/m^2·K)	2.65
Internal Walls (W/m^2·K)	1.71
Internal Floors (W/m^2·K)	0.16
Roof (W/m^2·K)	4.36
External Roof (W/m^2·K)	2.97
Glazing	©1 pane glazing, clear, 4

Table 10.27: Parameter values for height, floor area and occupancy used in IDA ICE to model the Basic building archetype.

Archetype	1 Basic
Building Average Height (m)	2.4
Modelled Building Height (m)	2.5
Number of Floors per Building	1
Building Average Floor Area (m^2)	65.2
Modelled Building Floor Area (m^2)	65
Number of Occupants per Building	4

Table 10.28: Parameters for Equipment and Lightning internal gains, Thermal conditioning systems and Energy efficiency measures applied in IDA ICE to model the Basic building archetype.

	Archetype	1 Basic
Scenario 1	**Equipment Power density (W/m^2)**	1.5
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	1.5
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	n/a
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	n/a
Scenario 2	**Equipment Power density (W/m^2)**	1.88
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	1.88
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	n/a
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	n/a
Scenario 3	**Equipment Power density (W/m^2)**	2.06
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	2.06
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	n/a
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	n/a

Table 10.29: Overall energy performance of the Basic archetype building.

	Archetype	1. Basic
Scenario 1	**Electricity Purchased by facility (kW/year)**	427.8
Scenario 2	**Electricity Purchased by facility (kW/year)**	534.7
Scenario 3	**Electricity Purchased by facility (kW/year)**	588.2

Block buildings

Table 10.30: Elements of construction U-values (W/m^2·K) used in IDA ICE to model the Block building archetype.

Archetype	2 Block
External Walls (W/m^2·K)	2.3
Internal Walls (W/m^2·K)	1.71
Internal Floors (W/m^2·K)	0.16
Roof (W/m^2·K)	1.27
External Roof (W/m^2·K)	2.9
Glazing	©1 pane glazing, clear, 4

Table 10.31: Parameter values for height, floor area and occupancy used in IDA ICE to model the Block building archetype.

Archetype	2 Block
Building Average Height (m)	2.7
Modelled Building Height (m)	2.5
Number of Floors per Building	1
Building Average Floor Area (m^2)	141.0
Modelled Building Floor Area (m^2)	140
Number of Occupants per Building	5

Table 10.32: Parameters for Equipment and Lightning internal gains, Thermal conditioning systems and Energy efficiency measures applied in IDA ICE to model the Block building archetype.

	Archetype	2 Block
Scenario 1	**Equipment Power density (W/m^2)**	1.8
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	3
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	n/a
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	n/a
Scenario 2	**Equipment Power density (W/m^2)**	2.25
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	3.75
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	n/a
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	n/a
Scenario 3	**Equipment Power density (W/m^2)**	1.8
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	3
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	Yes
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	Yes

Table 10.33: Overall energy performance of the Block archetype building.

	Archetype	2. Block
Scenario 1	**Electricity Purchased by facility (kW/year)**	921.3
Scenario 2	**Electricity Purchased by facility (kW/year)**	1 151.6
Scenario 3	**Electricity Purchased by facility (kW/year)**	1 112.5

Bungalow buildings

Table 10.34: Elements of construction U-values (W/m^2·K) used in IDA ICE to model the Bungalow building archetype.

Archetype	3 Bungalow
External Walls (W/m^2·K)	2.02
Internal Walls (W/m^2·K)	1.71
Internal Floors (W/m^2·K)	0.16
Roof (W/m^2·K)	1.27
External Roof (W/m^2·K)	2.9
Glazing	©1 pane glazing, clear, 4

Table 10.35: Parameter values for height, floor area and occupancy used in IDA ICE to model the Bungalow building archetype.

Archetype	3 Bungalow
Building Average Height (m)	3.6
Modelled Building Height (m)	3.5
Number of Floors per Building	1
Building Average Floor Area (m^2)	176.7
Modelled Building Floor Area (m^2)	175
Number of Occupants per Building	5

Table 10.36: Parameters for Equipment and Lightning internal gains, Thermal conditioning systems and Energy efficiency measures applied in IDA ICE to model the Bungalow building archetype.

	Archetype	3 Bungalow
Scenario 1	**Equipment Power density (W/m^2)**	4
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	3
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	Yes
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	n/a
Scenario 2	**Equipment Power density (W/m^2)**	5
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	3.75
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	Yes
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	Yes
Scenario 3	**Equipment Power density (W/m^2)**	5.5
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	4.13
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	Yes
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	Yes

Table 10.37: Overall energy performance of the Bungalow archetype building.

	Archetype	3. Bungalow
Scenario 1	**Electricity Purchased by facility (kW/year)**	1 939.7
Scenario 2	**Electricity Purchased by facility (kW/year)**	1 733.3
Scenario 3	**Electricity Purchased by facility (kW/year)**	1 900

Villa buildings

Table 10.38: Elements of construction U-values (W/m^2·K) used in IDA ICE to model the Villa building archetype.

Archetype	4 Villa
External Walls (W/m^2·K)	2.02
Internal Walls (W/m^2·K)	1.71
Internal Floors (W/m^2·K)	0.16
Roof (W/m^2·K)	1.27
External Roof (W/m^2·K)	2.9
Glazing	©1 pane glazing, clear, 4

Table 10.39: Parameter values for height, floor area and occupancy used in IDA ICE to model the Villa building archetype.

Archetype	4 Villa
Building Average Height (m)	4.5
Modelled Building Height (m)	5
Number of Floors per Building	2
Building Average Floor Area (m^2)	270.3
Modelled Building Floor Area (m^2)	270
Number of Occupants per Building	10

Table 10.40: Parameters for Equipment and Lightning internal gains, Thermal conditioning systems and Energy efficiency measures applied in IDA ICE to model the Villa building archetype.

	Archetype	4 Villa
Scenario 1	**Equipment Power density (W/m^2)**	0.5
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	0.75
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	Yes
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	n/a
Scenario 2	**Equipment Power density (W/m^2)**	0.625
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	0.94
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	Yes
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	Yes
Scenario 3	**Equipment Power density (W/m^2)**	0.69
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	1.03
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	Yes
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	Yes

Table 10.41: Overall energy performance of the Villa archetype building.

	Archetype	4. Villa
Scenario 1	**Electricity Purchased by facility (kW/year)**	2 897.1
Scenario 2	**Electricity Purchased by facility (kW/year)**	1 917.4
Scenario 3	**Electricity Purchased by facility (kW/year)**	2 036.5

Mid-rise buildings

Table 10.42: Elements of construction U-values (W/m^2·K) used in IDA ICE to model the Mid-rise building archetype.

Archetype	5 Mid-rise
External Walls (W/m^2·K)	2.02
Internal Walls (W/m^2·K)	1.71
Internal Floors (W/m^2·K)	0.16
Roof (W/m^2·K)	0.33
External Roof (W/m^2·K)	2.9
Glazing	©1 pane glazing, clear, 4

Table 10.43: Parameter values for height, floor area and occupancy used in IDA ICE to model the Mid-rise building archetype.

Archetype	5 Mid-rise
Building Average Height (m)	5.1
Modelled Building Height (m)	5
Number of Floors per Building	2
Building Average Floor Area (m^2)	619.0
Modelled Building Floor Area (m^2)	620.0
Number of Occupants per Building	100

Table 10.44: Parameters for Equipment and Lightning internal gains, Thermal conditioning systems and Energy efficiency measures applied in IDA ICE to model the Mid-rise building archetype.

	Archetype	5 Mid-rise
Scenario 1	Equipment Power density (W/m^2)	5
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	3
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	Yes
	Standard Air Handling Unit (CAV 1 L/s·m^2)	Yes
	External shading	n/a
Scenario 2	Equipment Power density (W/m^2)	6.25
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	3.75
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	Yes
	Standard Air Handling Unit (CAV 1 L/s·m^2)	Yes
	External shading	Yes
Scenario 3	Equipment Power density (W/m^2)	6.88
	Equipment Usage Schedule	© House lighting
	Lighting Power density (W/m^2)	4.13
	Lighting Usage Schedule	© House lighting
	Ideal Cooler	Yes
	Standard Air Handling Unit (CAV 1 L/s·m^2)	Yes
	External shading	Yes

Table 10.45: Overall energy performance of the Mid-rise archetype building.

	Archetype	5. Mid-rise
Scenario 1	Electricity Purchased by facility (kW/year)	44 220.7
Scenario 2	Electricity Purchased by facility (kW/year)	45 212.3
Scenario 3	Electricity Purchased by facility (kW/year)	48 044.9

Hall buildings

Table 10.46: Elements of construction U-values (W/m^2·K) used in IDA ICE to model the Hall building archetype.

Archetype	7 Hall
External Walls (W/m^2·K)	2.3
Internal Walls (W/m^2·K)	1.71
Internal Floors (W/m^2·K)	0.16
Roof (W/m^2·K)	1.27
External Roof (W/m^2·K)	2.9
Glazing	©1 pane glazing, clear, 4

Table 10.47: Parameter values for height, floor area and occupancy used in IDA ICE to model the Hall building archetype.

Archetype	7 Hall
Building Average Height (m)	3.8
Modelled Building Height (m)	4
Number of Floors per Building	1
Building Average Floor Area (m^2)	566.8
Modelled Building Floor Area (m^2)	570
Number of Occupants per Building	35

Table 10.48: Parameters for Equipment and Lightning internal gains, Thermal conditioning systems and Energy efficiency measures applied in IDA ICE to model the Hall building archetype.

	Archetype	7 Hall
Scenario 1	**Equipment Power density (W/m^2)**	50
	Equipment Usage Schedule	© 07 - 17 Weekdays
	Lighting Power density (W/m^2)	10
	Lighting Usage Schedule	© 07 - 17 Weekdays
	Ideal Cooler	n/a
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	n/a
Scenario 2	**Equipment Power density (W/m^2)**	62.5
	Equipment Usage Schedule	© 07 - 17 Weekdays
	Lighting Power density (W/m^2)	12.5
	Lighting Usage Schedule	© 07 - 17 Weekdays
	Ideal Cooler	n/a
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	n/a
Scenario 3	**Equipment Power density (W/m^2)**	50
	Equipment Usage Schedule	© 07 - 17 Weekdays
	Lighting Power density (W/m^2)	10
	Lighting Usage Schedule	© 07 - 17 Weekdays
	Ideal Cooler	Yes
	Standard Air Handling Unit (CAV 1 L/s·m^2)	n/a
	External shading	Yes

Table 10.49: Overall energy performance of the Hall archetype building.

	Archetype	7. Hall
Scenario 1	**Electricity Purchased by facility (kW/year)**	8 926.9
Scenario 2	**Electricity Purchased by facility (kW/year)**	11 157.9
Scenario 3	**Electricity Purchased by facility (kW/year)**	12 197.6

10.7 Economical assessment

COOKING

Start from 2030

Table 10.50: Projected Population by Year [33].

Year	Total Population
2023	510900
2024	533837
2025	557373
2026	581465
2027	606193
2028	631666
2029	657819
2030	684506
2031	711703
2032	739518
2033	768118.79
2034	797350.61
2035	827201.73
2036	857658.77
2037	888708.75
2038	920329.02
2039	952507.25
2040	985221.42
2041	1018449.8
2042	1052168.94
2043	1086353.69
2044	1120977.17
2045	1156100.81
2046	1191424.34
2047	1227185.83
2048	1263261.37
2049	1299616.75
2050	1336214.24

Table 10.51: Technologies Accounted in Each Scenario.

Scenario	LPG	Charcoal/Firewood	Biogas	Electric
1	YES	YES	NO	NO
2	YES	NO	YES	NO
3	YES	YES	NO	YES

Table 10.52: CAPEX per Cooking Technology [USD/unit] [32].

Tech	LPG	Firewood & Charcoal	Biogas	Electric
Cost	68.35	0	68.35	24.49

.

OPEX calculations HH = Household assumption: each household contains 3.52 people [33].

Numbers used:

- For LPG: 1,2 kg/(month*capita) [62].
- For LPG: 1,01 USD/kg [63].
- For Charcoal: 9 USD/(month*HH) [64].
- For Biogas: 0,73 USD/kg [65].
- For E-stoves: 0,59 kWh/(day*HH) [63].

LPG

$$1,2\frac{kg}{month*capita}*3,52\frac{people}{HH}*12months = 50,688\frac{kg}{HH*year}$$

$$1,01\frac{USD}{kg}*50,688\frac{kg}{HH*year} = 51,195\frac{USD}{year*HH}$$

Charcoal

$$9\frac{USD}{month*HH}*12months = 108\frac{USD}{HH*year}$$

Biogas

$$0,73\frac{USD}{kg}*1,214\frac{kg}{m^3}*0,972\frac{m^3}{day}*365days = 314,41\frac{USD}{year*HH}$$

E-stoves

$$0,59\frac{kWh}{day*HH}*365days*0,215\frac{USD}{year*HH} = 46,3\frac{USD}{year*HH}$$

Table 10.53: OPEX per Technology [USD/(year·HH)].

Tech	LPG	Charcoal & Firewood	Biogas	Electric
Cost	51.2	108	314.56	46.3

TRANSPORT - BUSES

Table 10.54: Technologies Accounted in Each Scenario.

Scenario	**Bio-buses**	**E-buses**	**Diesel buses**
1	NO	YES	YES
2	YES	NO	YES
3	NO	YES	YES

Table 10.55: CAPEX per Bus Type [USD/unit].

Tech	Bio-Buses	E-Buses [66]	Diesel Buses
Cost	318977.85 [67]	43387.89 [66]	288000 [68]

Calculations for OPEX

Numbers used:

- For Diesel: 1,13 USD/L [69]

Diesel

$$164\frac{km}{day} * 365 days * 0,461\frac{L}{km} * 1,13\frac{USD}{L} = 31182,87\frac{USD}{year}$$

Electrical buses

$$164\frac{km}{day} * 365 days * 0,215\frac{USD}{km} * 1\frac{kWh}{km} = 12869,9\frac{USD}{year}$$

Table 10.56: OPEX per Bus Type [USD/year], @ = counted in biodigester.

Tech	Bio-Buses	E-Buses	Diesel Buses
Cost	@	12869.9	31182.87

BIODIGESTER

CAPEX calculation Calculations resulted in a required volume of the digester of 20 755,85 m^3 [70]. The size of the selected digestor is 10 000 m^3 [71]. 3 digestors are accounted which results in a total volume of:

$$3 * 10000 = 30000m^3$$

Due to population and demand increase over time, it was aimed to account for a higher volume than necessary. The price for one digestor was estimated to be 62,5 USD/m^3 installed [72]. The total price is then:

$$62,5\frac{USD}{m^3} * 30000m^3 = 1875000USD$$

OPEX calculation The OPEX is 4% of the CAPEX value [73], which results in the annual value of:

$$1875000 * 0,04 = 75000\frac{USD}{year}$$

Table 10.57: Biodigester Costs [USD].

CAPEX	1875000 USD
OPEX	75000 USD/year