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MÁSTER UNIVERSITARIO EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

Modelling of the supply chain of LPG for clean cooking

Autor: Judith Serra Llavona

Director: Pablo Dueñas Martínez

Director: Eduardo Sánchez Jacob

Director: Fernando de Cuadra García

Madrid, agosto 2023

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Modelling of the supply chain of LPG for clean cooking en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

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RESUMEN DEL PROYECTO

MODELADO DE LA CADENA DE SUMINISTRO DE LPG PARA RWANDA

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Entidad Colaboradora: ICAI – Universidad Pontificia Comillas

ABSTRACT

El acceso a soluciones de *clean cooking* es una preocupación global, ya que las prácticas tradicionales de cocinado con combustibles sólidos contribuyen a la contaminación del aire en interiores y la degradación del medio ambiente. La adopción del Gas Licuado de Petróleo (GLP) como una alternativa para cocinar de manera limpia ha ganado impulso, lo que ha aumentado la necesidad de redes de distribución eficientes para garantizar su disponibilidad y accesibilidad.

La red de distribución de GLP desempeña un papel fundamental en facilitar la adopción generalizada de soluciones de *clean cooking*. Sin embargo, las complejidades de esta red, que involucran dinámicas de la cadena de suministro, logística de transporte, infraestructura de almacenamiento y mecanismos de fijación de precios, requieren un enfoque integral para la toma de decisiones. Este proyecto reconoce la importancia de estas decisiones y propone la creación de una herramienta que pueda analizar el impacto financiero de diversas opciones tomadas dentro del marco de distribución de GLP. En este proyecto, dicha herramienta se diseña, desarrolla y pone a prueba mediante la evaluación de diferentes escenarios.

La motivación principal detrás de este esfuerzo radica en abordar la necesidad de optimizar la eficiencia de la red de distribución. Al desarrollar una herramienta de evaluación de decisiones, los interesados, incluidos gobiernos, responsables de políticas y expertos de la industria, pueden tomar decisiones informadas. La capacidad de la herramienta para simular diferentes escenarios y proyectar las implicaciones de costes permite priorizar decisiones que se alineen con objetivos de sostenibilidad económica y ambiental.

Palabras clave: GLP, cadena de suministro, modelo de costes, red de distribución, cocina limpia, Ruanda.

1. Introducción

La cocina limpia es un componente vital del desarrollo sostenible, y su éxito se basa en la combinación estratégica de diversas tecnologías. Esta importancia se vuelve especialmente pronunciada en regiones en rápida transformación, como Ruanda, donde la transición de prácticas culinarias tradicionales ofrece promesas inmensas para avances sociales y ambientales multifacéticos (Bennitt, 2021; Pachauri, 2021). El compromiso de Ruanda con el progreso exige un enfoque integral que utilice óptimamente estas tecnologías. Al abordar las especificidades del GLP dentro de este marco más amplio, esta investigación tiene la intención de ofrecer perspectivas prácticas aplicables al panorama general de las soluciones de cocina limpia.

2. Definición del proyecto

El enfoque de esta investigación implica la construcción de un modelo de costes que desglose las complejidades de la cadena de suministro de GLP. El modelo servirá como una herramienta para analizar cómo diferentes decisiones en la cadena de suministro influyen en el costo general de establecer una red de distribución de GLP, un aspecto esencial de la adopción de la cocina limpia (Wright, 2020).

Dada la complejidad de las cadenas de suministro del mundo real, la investigación reconoce la necesidad de encontrar un equilibrio entre la profundidad analítica y la usabilidad práctica. Será necesario realizar suposiciones para simplificar la complejidad del modelo manteniendo su relevancia. Los insumos requeridos por el modelo y las estimaciones de parámetros fundamentan el análisis en datos tangibles, conectando la teoría con la aplicación en el mundo real.

La importancia práctica de esta investigación radica en su potencial para informar la toma de decisiones. Al examinar diversos escenarios, el estudio tiene como objetivo descubrir perspectivas aplicables a la formulación de políticas y estrategias de inversión.

3. Estado del arte

En naciones en desarrollo, incluyendo Ruanda, las tecnologías de cocina a menudo dependen de combustibles tradicionales como leña, carbón y residuos agrícolas (Hakizimana, 2020). Estos métodos convencionales, aunque arraigados en prácticas culturales, tienen considerables implicaciones sociales, ambientales y de salud causadas por la contaminación del aire en los hogares (Sánchez Jacob, 2021). Dado que el GLP quema de manera eficiente y las emisiones de contaminación al aire en los hogares causadas por él son mucho más bajas que las producidas por estufas de combustibles tradicionales, se considera una tecnología de cocina limpia.

Algunas organizaciones, como la Asociación Global de GLP (GLPGP), están trabajando para la transición al GLP, enfocándose en la expansión de las cadenas de suministro necesarias y convenciendo a los clientes de cambiar hacia él (GLPGP, 2023). El hecho es que el GLP no requiere el mismo nivel de inversión inicial en infraestructura que otras alternativas como la electricidad o el gas natural.

Aunque la optimización de la modelización de las cadenas de suministro ha sido un tema de estudio desde hace mucho tiempo, en tiempos recientes ha habido un interés renovado en ello, con el objetivo principal de reducir costes al mejorar la eficiencia de la red. Al modelar una red de distribución, se desarrollan modelos matemáticos, algoritmos de optimización y técnicas de simulación con el fin de contribuir al proceso de toma de decisiones al estudiar y evaluar una variedad de escenarios.

4. Definición del modelo

El objetivo de este modelo es obtener una comprensión integral de la estructura de costes en un entorno simplificado, para establecer una base sólida para un análisis posterior. Al simular una cadena de suministro lineal con una unidad de cada componente de infraestructura, se pueden identificar los factores clave de costes sin la complejidad introducida por múltiples instalaciones o interdependencias entre ellas.

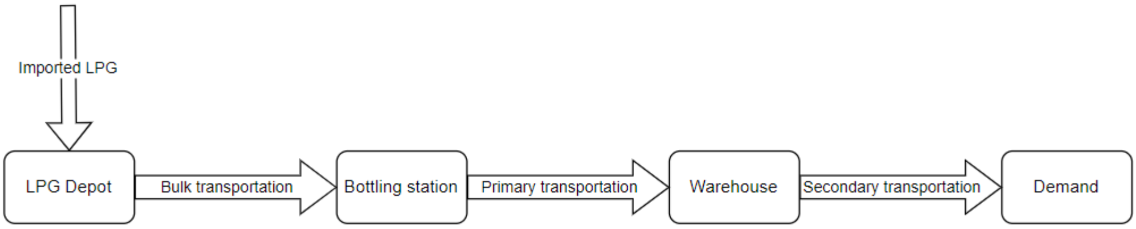


Figura 1. Estructura del modelo simple. Fuente: Elaboración propia.

La estructura lógica de la cadena de suministro simplificada de GLP, como se describió anteriormente, se representa en la Figura 1. Esta figura ilustra el flujo secuencial del GLP desde su importación a la región hasta el minorista, resaltando los componentes clave de la infraestructura y las rutas de transporte involucradas.

A continuación, se presentará el desglose de los costes anuales totales en este escenario simple. La siguiente ecuación, Eq. (1), presenta el cálculo de los costes generales. Como se puede observar, comprende los costes originados por los cilindros, los costes derivados del transporte total, los costes provenientes de la infraestructura total y los costes asociados con la importación de GLP en la región. Es relevante destacar que se utilizará un enfoque ascendente para calcular todos los costes dentro de la cadena de suministro. Este enfoque se adopta principalmente debido a la presencia de pérdidas que ocurren durante las diversas etapas del proceso. Las ecuaciones más representativas del modelo se muestran a continuación.

$$C_{tot} = C_{cyl} + C_{trans_{tot}} + C_{infra_{tot}} + C_{LPG_{imp}}$$

$C_{tot}: Coste\ total\ [\frac{USD}{año}]$
$C_{cyl}: Coste\ total\ de\ cilindros\ \left[\frac{USD}{año}\right]$
$C_{trans_{tot}}: Coste\ total\ de\ transporte\ [\frac{USD}{año}]$
$C_{infra_{tot}}: Coste\ total\ de\ transporte\ [\frac{USD}{año}]$
$C_{LPG_{imp}}: Coste\ del\ GLP\ importado\ \left[\frac{USD}{año}\right]$

$$C_{cyl} = \sum_{i=1}^{n_{size\ cyl}} C_{cyl_{acq_i}} = \sum_{i=1}^{n_{size\ cyl}} \frac{(Q_{cyl_i} * P_{cyl_{emp_i}}) * r}{[1 - (1 + r)^{-LT_{cyl_i}}]}$$

$C_{cyl_{acq_i}}: Coste\ de\ adquirir\ los\ cilindros\ de\ tamaño\ i\ \left[\frac{USD}{año}\right]$
$Q_{cyl_i}: Cantidad\ de\ cilindros\ de\ tamaño\ i\ [cilindros]$
$P_{cyl_{emp_i}}: Precio\ de\ los\ cilindros\ de\ tamaño\ i\ [\frac{USD}{cilindro}]$

r: *tasa de descuento* [%]
LT_{cyl_i}: *Vida útil de los cilindros de tamaño i* [año]
$n_{size\ cyl}$: *número de tamaños de cilindros considerados*

$$C_{trans_{tot}} = C_{sectrans} + C_{primtrans} + C_{bulktrans}$$

$C_{sectrans}$: *Coste del transporte secundario* $[\frac{USD}{año}]$
$C_{primtrans}$: *Coste del transporte primario* $[\frac{USD}{año}]$
$C_{bulktrans}$: *Coste del transporte a granel* $[\frac{USD}{año}]$

$$C_{sectrans} = C_{sectrans_{inv}} + C_{fuel_{sectrans}} + C_{sectrans_{FOM_{tot}}} + C_{sectrans_{VOM_{tot}}} + C_{sectrans_{lic}}$$

$C_{sectrans_{inv}}$: *Coste de adquisición de todos los vehículos secundarios* $\left[\frac{USD}{año}\right]$
$C_{fuel_{sectrans}}$: *Coste de todo el combustible de los vehículos secundarios* $\left[\frac{USD}{año}\right]$
$C_{sectrans_{FOM_{tot}}}$: *Costes de operación fijos de los vehículos secundarios* $[\frac{USD}{año}]$
$C_{sectrans_{VOM_{tot}}}$: *Costes de operación variables de los vehículos secundarios* $[\frac{USD}{año}]$
$C_{sectrans_{lic}}$: *Coste de las licencias de los vehículos secundarios* $[\frac{USD}{año}]$

$$C_{infra_{tot}} = C_{WH} + C_{BS} + C_{Dep}$$

C_{WH}: *Coste total de almacenes* $[\frac{USD}{año}]$
C_{BS}: *Coste total de embotelladoras* $[\frac{USD}{año}]$
C_{Dep}: *Coste total de depósito de GLP* $[\frac{USD}{año}]$

$$C_{WH} = C_{WH_{ON}} + C_{WH_{FOM_{tot}}} + C_{WH_{VOM_{tot}}} + C_{WH_{lic}}$$

$C_{WH_{ON}}$: *Coste de apertura de almacenes* $[\frac{USD}{año}]$
$C_{WH_{FOM_{tot}}}$: *Costes de operación fijos de almacenes* $[\frac{USD}{año}]$
$C_{WH_{VOM_{tot}}}$: *Costes de operación varibales de almacenes* $[\frac{USD}{año}]$
$C_{WH_{lic}}$: *Costes de las licencias de almacenes* $[\frac{USD}{año}]$

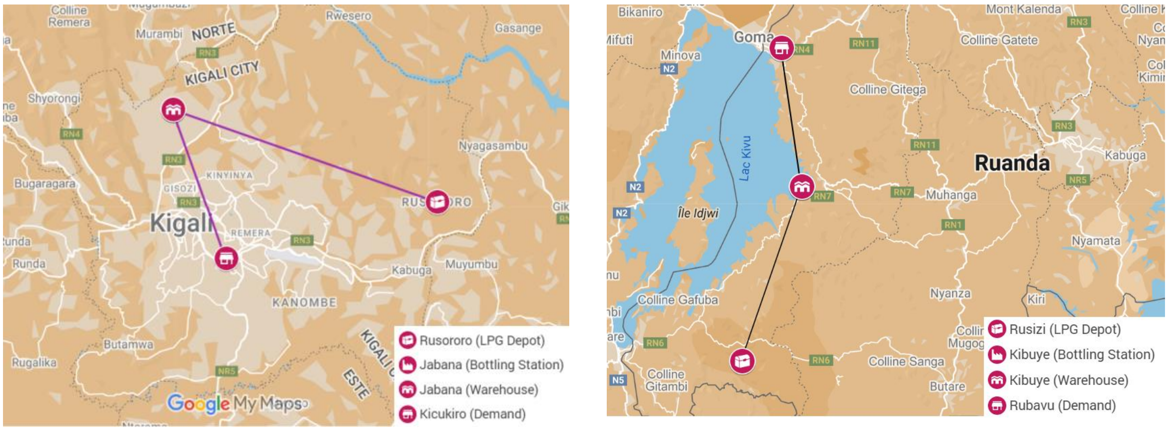
$$C_{LPG_{imp}} = Q_{LPG_{imp}} * P_{LPG}$$

$Q_{LPG_{imp}}$: *Cantidad total de GLP importado* $\left[\frac{ton}{año}\right]$
P_{LPG}: *Precio del GLP importado* $[\frac{USD}{ton}]$

5. Resultados

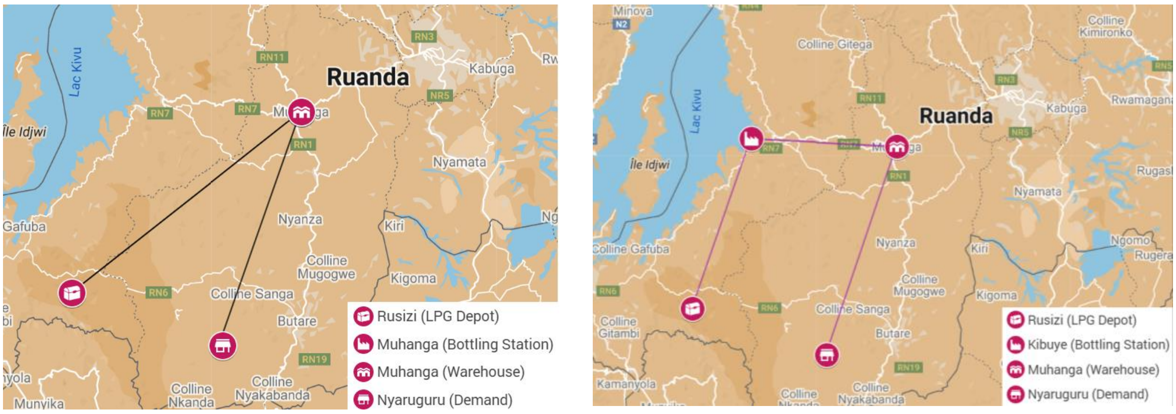
Una vez que se completó la modelización para cada una de las subsecciones, se evaluaron cuatro casos de muestra. Estos se utilizaron para evaluar el impacto de los datos de cada caso en el precio final del GLP. El primer escenario se centró en Kigali, la ciudad capital de Ruanda. El segundo escenario se enfocó en Rubavu, la segunda ciudad más grande del país. Esto se hizo para comparar los resultados con los obtenidos en el primer escenario y corregir el modelo si fuera necesario.

El segundo conjunto de escenarios se centró en Nyaruguru, una zona rural. El objetivo del tercer y cuarto escenario era comparar los efectos de diferentes configuraciones de la red, su impacto en la cadena de suministro y en el precio final. Por lo tanto, el tercer escenario no incluyó un almacén dedicado en la región, mientras que el cuarto escenario sí lo hizo. Los mapas de los cuatro escenarios se muestran a continuación en la Figura 2.



Kigali

Rubavu



Nyaruguru sin almacén

Nyaruguru con almacén

Figura 2. Mapa de la red de los casos. Fuente: Elaboración propia.

Los principales resultados para cada uno de los escenarios se muestran en la Tabla 1. El desglose de los costes por cilindro se muestra en la Figura 3.

Main Results	Kigali Case	Rubavu Case	Nyaruguru Case	Nyaruguru Case WH	Units
Total Cost of LPG Importation	7.770.592,16	2.182.469,46	1.101.423,04	1.101.423,04	[$/year]
Total Cost of Infrastructure	935.905,21	394.660,48	330.456,43	283.442,22	[$/year]
Total Cost of Transportation	166.545,64	91.667,77	52.648,72	70.250,73	[$/year]
Total Cost of Cylinders	227.274,32	63.824,30	37.804,64	37.804,64	[$/year]
Total Cost	**9.100.317,33**	**2.732.622,00**	**1.522.332,82**	**1.492.920,62**	**[$/year]**
Total Unitary Cost	**1.060,40**	**1.133,87**	**1.251,92**	**1.227,73**	**[$/year-ton]**
Total Cost Per Cylinder	**12,72**	**13,61**	**15,02**	**14,73**	**[$/year-cylinder]**

Tabla 1. Principales resultados del análisis de costes. Fuente: Elaboración propia.

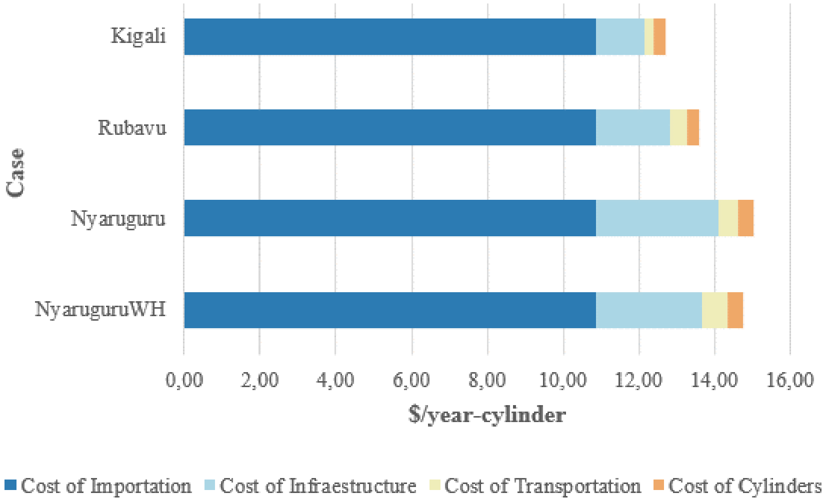


Figura 3. Desglose de costes por caso. Fuente: Elaboración propia.

6. Conclusiones

El examen detallado del modelo ha revelado ideas importantes sobre la futura red de distribución de GLP en Ruanda. Un hallazgo importante es el impacto de los costes de importación de GLP. Aunque estos no pueden ser influenciados internamente, negociar con los países proveedores de GLP podría marcar la diferencia en la gestión de estos gastos. Otro impacto es cómo cambian los costes de los cilindros según su rotación. En áreas urbanas densas, donde los cilindros se utilizan con más frecuencia, los costes se reducen. Pero en lugares más rurales donde la rotación de cilindros es menor, los costes aumentan ligeramente. Esto sugiere que un sistema de gestión de cilindros podría reducir el costo. Al observar los costes de infraestructura y transporte, estos varían según el caso estudiado. Están influenciados por la población total dentro de un área y el uso de la infraestructura. Centrándonos en los casos de Nyaruguru, hay una gran reducción de costes entre dos situaciones, causada por la implementación de un almacén en la zona. Al modelar un almacén independiente, los costes disminuyeron considerablemente.

Aunque el modelo de costes para la cadena de suministro de GLP en Ruanda ha demostrado ser valioso, es crucial reconocer sus simplificaciones inherentes. Estas simplificaciones fueron necesarias para crear un marco analítico práctico, pero también presentan oportunidades para futuras investigaciones que mejoren la precisión y aplicabilidad del modelo. Mirando hacia adelante, se pueden explorar varias vías de investigación futura para refinar y expandir el modelo de costes. En última instancia, la investigación continua contribuye a la distribución efectiva de GLP en toda Ruanda, avanzando en sus objetivos energéticos y beneficiando a su población.

7. Referencias

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SUMMARY OF THE PROJECT

MODELLING OF THE SUPPLY CHAIN OF LPG FOR CLEAN COOKING

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Collaborating Entity: ICAI – Universidad Pontificia Comillas

ABSTRACT

Access to clean cooking solutions is a paramount global concern, as traditional cooking practices using solid fuels contribute to indoor air pollution and environmental degradation. The adoption of Liquified Petroleum Gas (LPG) as a clean cooking alternative has gained momentum, prompting the need for efficient distribution networks to ensure its availability and affordability.

The LPG distribution network plays a pivotal role in facilitating the widespread adoption of clean cooking solutions. However, the complexities of this network, involving supply chain dynamics, transportation logistics, storage infrastructure, and pricing mechanisms, necessitate a comprehensive approach to decision-making. This project recognizes the significance of these decisions and proposes the creation of a tool that can analyze the financial impact of various choices made within the LPG distribution framework. In this project said tool is designed, developed, and tested by evaluating different case scenarios.

The primary motivation behind this endeavor lies in addressing the critical need to optimize the distribution network's efficiency while ensuring the affordability of clean cooking solutions for end-users. By developing a decision evaluation tool, stakeholders, including governments, policymakers, and industry experts, can make informed choices. The tool's ability to simulate different scenarios and project cost implications will enable stakeholders to prioritize decisions that align with both economic and environmental sustainability goals.

Keywords: LPG, supply chain, cost model, distribution network, clean cooking, Rwanda.

1. Introduction

Clean cooking is a vital component of sustainable development, and its success relies on the strategic combination of diverse technologies. This emphasis becomes particularly pronounced in regions undergoing rapid transformation, such as Rwanda, where the transition from traditional cooking practices holds immense promise for multifaceted societal and environmental advancements (Bennitt, 2021; Pachauri, 2021). Rwanda's commitment to progress necessitates a comprehensive approach that optimally utilizes these technologies. By addressing the specificities of LPG within this broader framework, this research intends to offer practical insights applicable to the larger landscape of clean cooking solutions.

2. Project definition

The focus of this research involves constructing a cost model that dissects the intricacies of the LPG supply chain. The model will serve as a tool to analyze how different supply chain decisions influence the overall cost of establishing a distribution network for LPG, an essential aspect of clean cooking adoption (Wright, 2020).

Given the complexity of real-world supply chains, the research acknowledges the need to strike a balance between analytical depth and practical usability. Assumptions will be necessary to streamline the model's complexity while maintaining its relevance. The inputs required by the model and their parameter estimations ground the analysis in tangible data, bridging theory with real-world application.

The practical significance of this research lies in its potential to inform decision-making. By examining various scenarios, the study aims to uncover insights applicable to policy formulation and investment strategies.

3. State of Art

In developing nations, including Rwanda, cooking technologies often rely on traditional biomass fuels such as firewood, charcoal, and agricultural residues (Hakizimana, 2020). These conventional methods, while deeply ingrained in cultural practices, have considerable social, environmental, and health implications caused by household air pollution (Sánchez Jacob, 2021). Since LPG burns in an efficient manner, and the emissions of pollution to household air caused by it are far lower than those produced by traditional fuel stoves, it is considered as a clean cooking technology.

Some organizations, such as the Global LPG Partnership (GLPGP) are working towards the transition to LPG, working on the expansion of the needed supply chains and convincing customers to change towards it. (GLPGP, 2023). The facts that LPG does not require the same level of initial investment into infrastructure as other alternatives as electricity or natural gas.

Even though the modeling optimization of supply chains has been a topic of study since a long time ago, in recent times there has been a renewed interest in it, with the objective mainly of reducing costs by improving the efficiency of the network. When modeling a distribution network, mathematical models, optimization algorithms and simulation techniques are developed in order to contribute to the decision-making process by studying and evaluating an array of scenarios.

4. Model description

The objective of this model is to gain a comprehensive understanding of the cost structure in a simplified setting, to establish a solid foundation for further analysis. By simulating a linear supply chain with one unit of each infrastructure component, the key cost factors can be identified without the complexity introduced by multiple facilities or interdependencies among them.

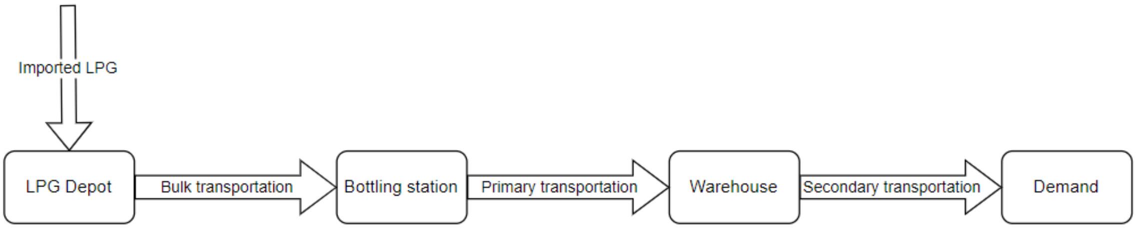


Figure 1. Simple model's structure. Source: Own elaboration.

The logical structure of the simplified LPG supply chain, as previously described, is depicted in Figure 1. This figure illustrates the sequential flow of LPG from its importation into the region to the retailer, highlighting the key infrastructure components and transportation routes involved.

Next, the breakdown of the total annual costs in this simple scenario will be presented. The following equation, Eq. (1), presents the computation of the overall costs. As it can be observed, it comprises costs originating from cylinders, costs arising from total transportation, costs stemming from total infrastructure, and costs associated with LPG importation in the region. It is relevant to highlight that a bottom-up approach will be used to calculate all the costs within the supply chain. This approach is adopted primarily due to the presence of losses that occur during the various stages of the process. The most representative equations of the model are shown below.

$$C_{tot} = C_{cyl} + C_{trans_{tot}} + C_{infra_{tot}} + C_{LPG_{imp}}$$

$C_{tot}: Total\ cost\ [\frac{USD}{year}]$
$C_{cyl}: Total\ cost\ of\ cylinders\ [USD/year]$
$C_{trans_{tot}}: Total\ cost\ of\ transportation\ [\frac{USD}{year}]$
$C_{infra_{tot}}: Total\ cost\ of\ infraestructure\ [\frac{USD}{year}]$
$C_{LPG_{imp}}: Cost\ of\ LPG\ imported\ \left[\frac{USD}{year}\right]$

$$C_{cyl} = \sum_{i=1}^{n_{size\ cyl}} C_{cyl_{acq_i}} = \sum_{i=1}^{n_{size\ cyl}} \frac{(Q_{cyl_i} * P_{cyl_{emp_i}}) * r}{[1-(1+r)^{-LT_{cyl_i}}]}$$

$C_{cyl_{acq_i}}: Cost\ of\ acquiring\ all\ cylinders\ size\ i\ \left[\frac{USD}{year}\right]$
$Q_{cyl_i}: Quantity\ of\ cylinders\ size\ i\ [cylinders]$
$P_{cyl_{emp_i}}: Price\ of\ empty\ cylinders\ size\ i\ [\frac{USD}{cylinder}]$
$r: discount\ rate\ [\%]$
$LT_{cyl_i}: Lifetime\ of\ cylinder\ size\ i\ [years]$
$n_{size\ cyl}: number\ of\ cylinder's\ sizes\ considered$

$$C_{trans_{tot}} = C_{sectrans} + C_{primtrans} + C_{bulktrans}$$

$C_{sectrans}: Cost\ of\ secondary\ transportation\ [\frac{USD}{year}]$
$C_{primtrans}: Cost\ of\ primary\ transportation\ [\frac{USD}{year}]$
$C_{bulktrans}: Cost\ of\ bulk\ transportation\ [\frac{USD}{year}]$

$$C_{sectrans} = C_{sectrans_{inv}} + C_{fuel_{sectrans}} + C_{sectrans_{FOM_{tot}}} + C_{sectrans_{VOM_{tot}}} + C_{sectrans_{lic}}$$

$C_{sectrans_{inv}}: Cost\ of\ acquiring\ all\ secondary\ vehicles\ \left[\frac{USD}{year}\right]$
$C_{fuel_{sectrans}}: Cost\ of\ all\ the\ fuel\ used\ by\ secondary\ vehicles\ \left[\frac{USD}{year}\right]$
$C_{sectrans_{FOM_{tot}}}: FOM\ of\ all\ secondary\ vehicle\ [\frac{USD}{year}]$

$C_{sectrans_{VOM_{tot}}}: VOM\ of\ all\ secondary\ vehicles\ [\frac{USD}{year}]$
$C_{sectrans_{lic}}: Cost\ of\ seconday\ transportation\ licenses\ [\frac{USD}{year}]$

$$C_{infra_{tot}} = C_{WH} + C_{BS} + C_{Dep}$$

$C_{WH}: Total\ cost\ of\ warehouses\ [\frac{USD}{year}]$
$C_{BS}: Total\ cost\ of\ bottling\ stations\ [\frac{USD}{year}]$
$C_{Dep}: Total\ cost\ of\ LPG\ Depots\ [\frac{USD}{year}]$

$$C_{WH} = C_{WH_{ON}} + C_{WH_{FOM_{tot}}} + C_{WH_{VOM_{tot}}} + C_{WH_{lic}}$$

$C_{WH_{ON}}: Cost\ of\ opening\ a\ new\ warehouse\ [\frac{USD}{year}]$
$C_{WH_{FOM_{tot}}}: FOM\ of\ all\ warehouses\ [\frac{USD}{year}]$
$C_{WH_{VOM_{tot}}}: VOM\ of\ all\ warehouses\ [\frac{USD}{year}]$
$C_{WH_{lic}}: Cost\ of\ warehouse's\ licenses\ [\frac{USD}{year}]$

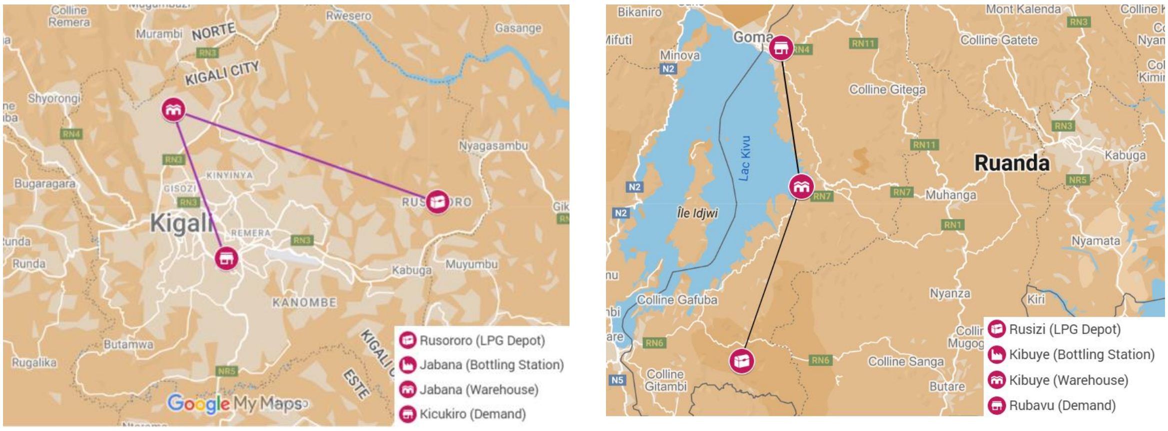
$$C_{LPG_{imp}} = Q_{LPG_{imp}} * P_{LPG}$$

$Q_{LPG_{imp}}: Total\ amount\ of\ LPG\ imported\ needed\ \left[\frac{MT}{year}\right]$
$P_{LPG}: Price\ of\ imported\ LPG\ [\frac{USD}{MT}]$

5. Results

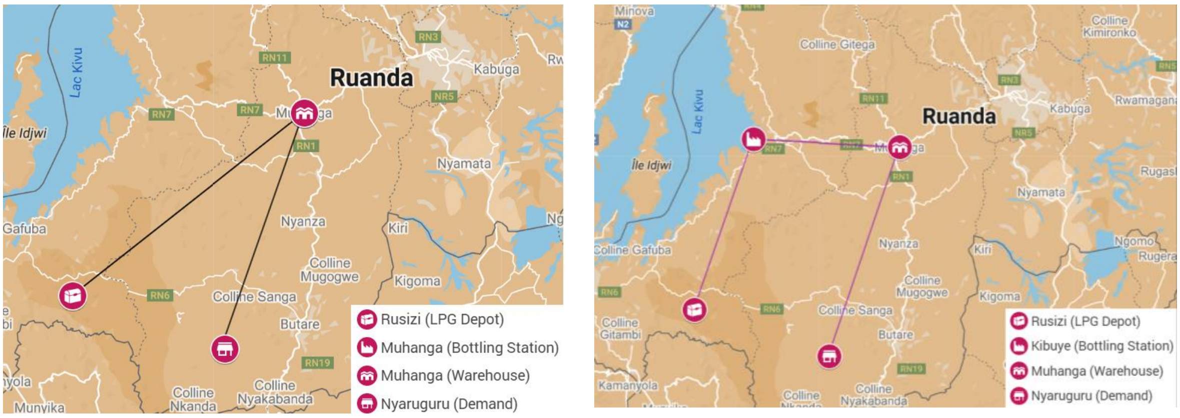
Once the modelling for each of the subsection was completed, four sample cases were evaluated. These were used to assess the impact of the case data on the final LPG price. The first scenario was centred on Kigali, Rwanda’s capital city. The second scenario focused on Rubavu, the second largest city in the country. This was done to compare the results with those obtained in the first scenario and correct the model if needed.

The second set of scenarios were instead focused on Nyaruguru, a rural area. The goal of the third and fourth scenarios was to compare the effects of different network configurations, its impact on the supply chain and on the final price. Therefore, the third scenario did not include a dedicated warehouse in the region, whereas the fourth scenario did. The maps of the four scenarios are shown below in Figure 2.



Kigali

Rubavu



Nyaruguru without warehouse

Nyaruguru with warehouse

Figure 2. Map of Cases' network. Source: Own elaboration.

The main results for each of the scenarios are shown in Table 1. The breakdown in per cylinder costs is shown in Figure 3

Main Results	Kigali Case	Rubavu Case	Nyaruguru Case	Nyaruguru Case WH	Units
Total Cost of LPG Importation	7.770.592,16	2.182.469,46	1.101.423,04	1.101.423,04	[$/year]
Total Cost of Infrastructure	935.905,21	394.660,48	330.456,43	283.442,22	[$/year]
Total Cost of Transportation	166.545,64	91.667,77	52.648,72	70.250,73	[$/year]
Total Cost of Cylinders	227.274,32	63.824,30	37.804,64	37.804,64	[$/year]
Total Cost	**9.100.317,33**	**2.732.622,00**	**1.522.332,82**	**1.492.920,62**	**[$/year]**
Total Unitary Cost	**1.060,40**	**1.133,87**	**1.251,92**	**1.227,73**	**[$/year-ton]**
Total Cost Per Cylinder	**12,72**	**13,61**	**15,02**	**14,73**	**[$/year-cylinder]**

Table 1. Main of results of cost analysis. Source: Own elaboration.

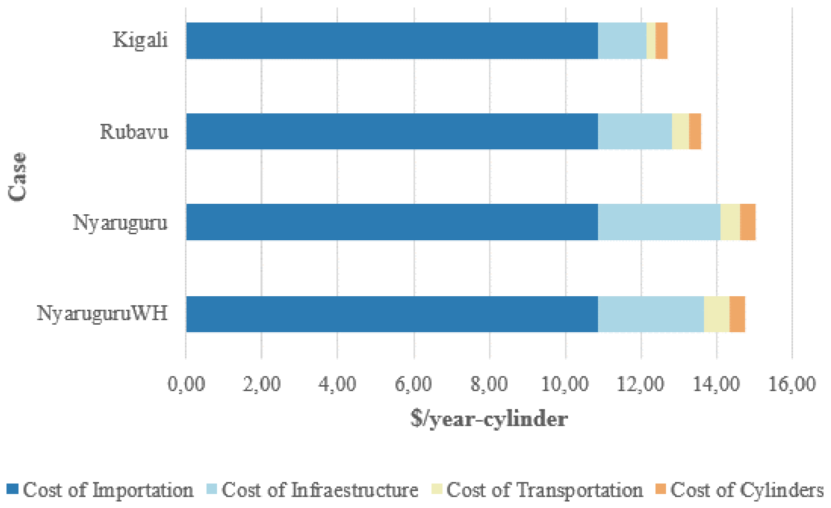


Figure 3. Cost breakdown by case. Source: Own elaboration.

6. Conclusions

The examination of the model's details has revealed some important insights about Rwanda's future LPG distribution network. One major finding is the impact of the LPG importation costs. While these can't be impacted internally, negotiating with the countries that supply the LPG could make a difference in managing these expenses. Another impact is how cylinder costs change depending on their turnover. In dense city areas, where the cylinders see more frequent use, the costs are reduced. But in more rural places where the cylinder turnover is lower, the costs increase slightly. This suggests that a cylinder management system could reduce the cost. Looking at infrastructure and transportation costs, these vary based on the case studied. These are impacted by the total population within an area as well as infrastructure usage. Focusing on the Nyaruguru cases, there is a big drop in costs between two situations, caused by the implementation of a warehouse within the area. By modelling an independent warehouse, costs dropped considerably.

While the cost model for the LPG supply chain in Rwanda has proven valuable, it is crucial to acknowledge its inherent simplifications. These simplifications were necessary to create a practical analytical framework, but they also present opportunities for further research to enhance the model's accuracy and applicability. Looking forward, several avenues for future research can be explored to refine and expand the cost model. Ultimately, ongoing research contributes to the effective distribution of LPG across Rwanda, advancing its energy goals and benefiting its population.

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Capítulo 1. INTRODUCTION

1.1 CONTEXT

Clean cooking, characterized by the adoption of modern energy sources such as liquid petroleum gas (LPG), electricity, and piped gas in technologically advanced stoves, has emerged as a pivotal focal point within the realm of sustainable development. This emphasis becomes particularly pronounced in regions undergoing rapid transformation, such as Rwanda, where the transition from traditional cooking practices holds immense promise for multifaceted societal and environmental advancements. The profound impact of clean cooking is encapsulated in a definition: the utilization of contemporary fuels to power modern stoves, thereby significantly mitigating household pollution (Bennitt, 2021; Pachauri, 2021).

As of the latest estimates, an alarming disparity persists, with approximately 4 billion individuals worldwide lacking access to clean cooking services that are both reliable and financially feasible. This staggering statistic underscores the urgency to address the glaring gap in access to cleaner cooking alternatives. Equally concerning, and perhaps more gravely, is the realization that over 2.31 million premature deaths are attributed to household air pollution stemming from the use of conventional cookstoves (Sánchez Jacob, 2021). Such dire consequences underscore the imperative of finding viable solutions to counteract the detrimental effects of traditional cooking methods.

However, the challenge transcends health-related implications. Conventional cooking practices are intertwined with a range of socio-environmental issues. The time-intensive process of sourcing raw materials, predominantly wood, for cooking is emblematic of inefficiency and drudgery. Post-cooking, the need for thorough cleaning further adds to the labor-intensive nature of these practices. Beyond the immediate household, these practices exert pressure on the environment, exacerbating deforestation and contributing to the intricate web of climate change challenges. Moreover, the gender implications are inescapable, with women disproportionately burdened by fuelwood collection, cooking, and cleaning duties, culminating in an asymmetrical exposure to the detrimental impacts of household air pollution. Simultaneously, women are constrained in their opportunities for broader engagement due to these demanding responsibilities.

Emerging as a beacon of hope within this complex landscape is the gradual shift towards electricity for cooking (eCooking) in economies with low to middle income. However, progress in this domain remains unequal and relatively slow, particularly in comparison to their high-income counterparts. Recognizing the incremental nature of this transition, the current approach emphasizes the integration of intermediary technologies, with LPG as a pivotal contender, to facilitate a gradual yet steady move towards cleaner cooking solutions. The coexistence of various technologies underscores a pragmatic understanding of the real-world dynamics involved in transitioning cooking practices on a large scale.

The foundation for this transformative journey lies in the development of an integrated clean cooking plan. A comprehensive framework is required to model and design supply chains encompassing a spectrum of cooking technologies, including electricity, LPG, charcoal, and others. To this end, an adoption model is equally indispensable, guiding the transition process toward a universally embraced paradigm of 100% clean cooking. This study seeks to contribute significantly to this transition by dissecting the nuances of the LPG supply chain's cost model in Rwanda. By doing so, it not only enriches the theoretical understanding of supply chain economics but also aligns seamlessly with Rwanda's commitment to sustainable development, fostering cleaner environments, and ultimately, uplifting public health standards.

This project is firmly grounded in the framework of the United Nations' Sustainable Development Goals (SDGs), which provide a clear roadmap for meaningful initiatives. Specifically, this project aligns with Goal 7.1, aiming to achieve universal access to affordable, reliable, and modern energy services by 2030 (SGDS, n.d.). This objective resonates strongly with the core mission of promoting clean cooking and the project focuses on promoting the adoption of modern energy sources, like LPG, which directly contribute to the realization of said goal.

1.2 MOTIVATION

This study is driven by the need to holistically understand and integrate various clean cooking technologies to formulate an effective plan for Rwanda. Among these technologies, the analysis of liquefied petroleum gas (LPG) takes center stage within the context of this research.

Clean cooking is a vital component of sustainable development, and its success relies on the strategic combination of diverse technologies. Rwanda's commitment to progress necessitates a comprehensive approach that optimally utilizes these technologies. By addressing the specificities of LPG within this broader framework, this research intends to offer practical insights applicable to the larger landscape of clean cooking solutions.

The focus of this research involves constructing a cost model that dissects the intricacies of the LPG supply chain. The model will serve as a tool to analyze how different supply chain decisions influence the overall cost of establishing a distribution network for LPG, an essential aspect of clean cooking adoption. While LPG is the focal point, the implications extend to other clean cooking technologies, making the study relevant to the overarching goal of cleaner cooking practices.

Given the complexity of real-world supply chains, the research acknowledges the need to strike a balance between analytical depth and practical usability. Assumptions will be necessary to streamline the model's complexity while maintaining its relevance. The inputs required by the model and their parameter estimations ground the analysis in tangible data, bridging theory with real-world application.

The practical significance of this research lies in its potential to inform decision-making. By examining various scenarios, the study aims to uncover insights applicable to policy formulation and investment strategies. This research thus transcends the realm of theory, presenting actionable insights that align with Rwanda's sustainable development aspirations.

Capítulo 2. STATE OF THE ART

2.1 OVERVIEW OF COCKING TECHNOLOGIES

2.1.1 CURRENT LANDSCAPE

In developing nations, including Rwanda, cooking technologies often rely on traditional biomass fuels such as firewood, charcoal, and agricultural residues (Hakizimana, 2020). These conventional methods, while deeply ingrained in cultural practices, have considerable social, environmental, and health implications. This section provides an overview of the prevailing cooking technologies and their impact on the well-being of individuals and the environment.

Firewood remains a dominant cooking fuel in many developing nations, including Rwanda. Easily accessible and often collected locally, firewood is a cost-effective option for households with limited resources. However, the extensive reliance on firewood has led to deforestation, soil degradation, and habitat loss (Clean cooking Alliance, 2015). Additionally, the inefficient combustion of firewood releases substantial amounts of pollutants and particulate matter, contributing to indoor air pollution and associated health risks (Ye, 2020).

Charcoal production and use constitute another prevalent cooking method in developing countries. Charcoal is created through the carbonization of wood or agricultural residues, resulting in a more energy-dense and portable fuel compared to firewood (Demirbas, 2016). However, the process of charcoal production contributes to deforestation and emits greenhouse gases. The combustion of charcoal in traditional stoves also produces indoor air pollutants, jeopardizing the respiratory health of those exposed (Shen, 2021).

Traditional cookstoves, often used in conjunction with firewood or charcoal, are prevalent in developing nations. These stoves are generally rudimentary and lack efficiency in fuel utilization. Consequently, they release harmful emissions such as carbon monoxide and fine particulate matter. The adverse effects of these emissions disproportionately impact women and children, who spend significant time in proximity to the stoves (Campbell, 2021).

The reliance on these conventional cooking technologies has significant health repercussions. Household air pollution resulting from inefficient combustion contributes to respiratory diseases, cardiovascular ailments, and other health issues, particularly among women and children who spend substantial time near cooking areas. The World Health Organization (WHO) identifies household air pollution as a major health risk, accounting for a substantial portion of premature deaths in developing nations.

A significant aspect within the context of clean cooking and sustainable energy access is the concept of "stacking of fuels." Stacking of fuels refers to the practice of using multiple energy sources in a complementary manner to fulfil varying energy needs. By combining different energy sources households and communities can optimize energy usage based on specific tasks and requirements (Ado et al., 2016). The rationale behind adopting the practice of fuel stacking is underscored by several factors. As new technologies emerge, they might not adequately fulfil non-cooking energy needs, prompting users to resort to a combination of sources. This necessity is further accentuated by the inherent limitations of individual cooking devices which may struggle to cater to all stove applications and cooking requirements (Yaday et al., 2021).

2.1.2 LPG

LPG stands for "Liquefied Petroleum Gas." It is a flammable hydrocarbon gas mixture that is used as fuel in various applications. LPG primarily consists of propane and butane, or a mixture of these gases, and it is obtained from the refining of crude oil or natural gas processing (Synák, 2019).

LPG is often used as a fuel for heating, cooking, and as an alternative to gasoline for vehicles. It is stored in liquid form under moderate pressure, which makes it easy to transport and store. When released from its container, LPG vaporizes and turns back into gas, which can then be used as fuel in various combustion-based systems (Raslavičius, 2014).

Since LPG burns in an efficient manner, and the emissions of pollution to household air caused by it are far lower than those produced by traditional fuel stoves, it is considered as a clean cooking technology. The possibility of being stored, used in an easy way and economically transported within densely populated, endowed with infrastructure, areas are some of the reasons why it is commonly used by urban households in low and middle-income nations.

But even so, when comparing the use of LPG to other traditional technologies, such as coal or firewood, the initial costs, as well as the operating cost are higher. One of the reasons for it is the fact that the transportation of LPG cylinders can be found challenging for some regions where supply chains are yet to reach and, therefore, that presented an inadequate infrastructure. (Wright, 2020)

Some organizations, such as the Global LPG Partnership (GLPGP) are working towards the transition to LPG, working on the expansion of the needed supply chains and convincing customers to change towards it. (GLPGP, 2023). The facts that LPG does not require the same level of initial investment into infrastructure as other alternatives as electricity or natural gas, and that simultaneously reduces the risks related to the health of those in the household, makes it a great alternative for rural population.

WLPGA found that in the year 2021, the global demand for LPG reached an impressive 316.9 million tons, showcasing its widespread significance. This demand was predominantly driven by three major markets: China, the United States, and India, signifying their pivotal roles in the LPG landscape. A noteworthy aspect of this demand is that around half of it was attributed to household consumption. This highlights the substantial reliance on LPG for cooking and heating purposes in residential settings across the globe. Additionally, the solid chemical sector contributed significantly, accounting for 28% of the total consumption (WLPGA, 2021).

2.1.3 ELECTRICITY

The use of electrical energy for cooking purposes can be seen as the final aim of clean cooking. However, nowadays, it can only be achieved in some high-income countries. The reason for it is that a high level of electrification is needed in order to be achieved, and those rates are yet only present in industrialized countries. As an example, in the US the cooking technology with a higher presence was the electric cookstove, being the most-used range fuel in more than half of the housing units (EIA, 2023). On the other hand, in less developed countries, such as Rwanda, the number of households that use electricity as the primary cooking fuel is considered to be 0.19%

(Bisaga & Menyeh, 2022), among other reasons due to its price and the challenging supply chain infrastructure needed.

Furthermore, the cost of electric stoves can be significantly high for low-income house units, since the prices might vary from 15 to 80 USD for electric hot plates, to 25 to 100 USD for induction stoves (Ramana Putti, Tsan, Mehta, & Kammil, 2015).

Cooking with electricity is a convenient and clean method that produces no emissions into the home or damaging smoke during the cooking process, which means that it is associated with low direct risks for health. It is also important to be considered that how beneficial is the technology depends on which fuels are used to generate the electricity that is being used for cooking, since the impact will be different in countries with a heavily coal-based generation mixed to those who lean more into renewable energies for example (Ramana Putti, Tsan, Mehta, & Kammil, 2015).

Nonetheless, the central objective driving the transition to clean cooking is the substantial improvement of sanitary conditions. This entails a concerted effort to diminish the emission of air pollutants that arise during the cooking process. One promising avenue for achieving this goal is the widespread adoption of e-cooking technologies. This shift to e-cooking holds immense potential for positively influencing the health and well-being of a substantial portion of the global population. The collective effect of reduced air pollutants from cooking can significantly alleviate respiratory and other health issues that currently afflict millions of individuals. In essence, the move towards cleaner cooking practices not only addresses the environmental impact but also carries the profound promise of safeguarding and enhancing the health of countless people.

2.2 MODELLING PROCESS OF SUPPLY CHAINS

Supply chain management and optimization are key aspects of many sectors, such as the LPG industry. The LPG supply chain is a complex network that includes all the processes from the production of gas, from raw LPG to its storage and distribution to end users.

Even though the modeling optimization of supply chains has been a topic of study since a long time ago, in recent times there has been a renewed interest in it, with the objective mainly of reducing costs by improving the efficiency of the network.

When modeling a distribution network, mathematical models, optimization algorithms and simulation techniques are developed in order to contribute to the decision-making process by studying and evaluating an array of scenarios. These tools are applied to different facets of the LPG supply chain, for example, inventory management, demand forecasting or transportation logistics. Moreover, in recent years the environmental impact of the supply chain has also become a subject of study when modeling the distribution network.

The aim of this section is to provide an overview of the state of the art on supply chain modeling, focusing on the LPG supply chain, to gain some insight about the problems and opportunities that are presented in the process, as well as the methods and approaches previously applied to face it.

Lopes (2020) puts the focus on the reverse logistic, particularly in the returns of used cylinders that need to be refilled. Reverse logistics is the process of organizing the return movement of items from the end users to the origin point or a disposal point (Quesada 2003). Lopes (2020) addresses that traditional inventory models, such as the Wilson model, do not take into consideration the role of reverse logistic in the supply chain. Said models focus on obtaining the EOQ (economic quantity order), the optimal batch size that allows to minimize the costs of inventory management, without considering the returns or disposals (Agarwal, 2014).

Aiming to address the specific elements of the process of returning the cylinders and refilling them, Lopes (2020) offers three modeling solutions. The first one takes into account a constant deterministic demand. The second one is a particularization of the first case in which the returned cylinders on their owned are able to satisfy the whole demand. And, lastly, a third one that takes into account that both the demand and the cylinders returned are of stochastic nature.

Murdapa (2022) describes the modelling approach of dynamic systems in which the amount of LPG cylinders is considered constant within the logistic chain system. Therefore, reverse logistic is considered by taking into account the cylinders returned. Moreover, it is also taken into consideration that customers are able to acquire their cylinders from different stores, meaning that they are not limited to a single distribution point. This is modelled using Bernoulli distributions.

Masudin (2015) designed a location-allocation model, comprising four tiers using the LINGOoptimisa software. The model considered both fixed and inventory costs, as well as transportation costs. Mixed Integer Linear Programming (MILP) was used to formulate the model and branch and bound techniques were applied to solve it.

Moreover, Santoso (2015) focuses on the modelling of a distribution chain of 3 kg LPG cylinders. In the model, each cylinder filling station is considered to be able to serve more than one distributor. Also, each distributor can acquire cylinders from multiple filling stations. However, despite the fact that each distributor is allowed to serve multiple points of sale, each point of sale can only be served by a single distributor. Furthermore, regarding transportation, the model considers the assumption that each distributor has a particular number of vehicles, each of them with a ser number of cylinders that can be delivered to the various points of sale using said vehicle. The model is focused on how to minimize the whole cost of the distribution network, taking into consideration both fixed and variable expenses of the cylinders filling stations, points of sales and distributors.

The goal of Meskarian (2017) is to estimate the appropriate number and geographic placement of clinics based on current demand and future project in order to reduce commute time of the clients of these facilities. In order to obtain the optimal clinic locations, a location-allocation model is used. This model entails picking a set of potential locations and geographically assigned demand sets to them.

To achieve this, Meskarian (2017) uses a discrete location model, in which is assumed that the demand can be aggregated into a discrete finite number of points, as well as that the potential locations are a discrete and known number of points. In the research the p-median model is mentioned as a discrete model that uses the weighted distance from each demand point to each potential location and aims to minimize that value. However, the main issue with the p-median model is that it might result in unrealistic long distance to some users.

Assuming that demand is considered satisfied just in the cases when it can be met within a limited time frame, Meskarian (2017) explains that the current literature is divided into two categories. The first one is those problems that require a minimum coverage level and aim to minimize the cost of achieving said coverage. The second one is the kind of problems which try to find the optimal coverage that minimizes the cost of coverage, these are called MCP (Maximal Covering Problems). In those latter models, MCP, one of the main hypotheses is that coverage is the binary type.

Meskarian (2017) focuses on a variation of the MCP model with the goal of location selection (given a maximum number of locations allowed) to cover the clients demand considering a set maximum travel time for them. GIS (Maptitude) software is used to estimate travel times using a private vehicle and Google API used to estimate travel time using public transportation. It is important to highlight that a limitation present is the model is the lack of consideration of clinics’ capacity.

Capítulo 3. MODELLING THE LPG SUPPLY CHAIN

3.1 OVERVIEW OF THE LPG SUPPLY CHAIN

Liquefied petroleum gas, also abbreviated as LPG, is a multipurpose fuel which can be employed for a variety of purposes including heating, cooking, and operating machinery. The LPG distribution network is a multi-stage process that goes from production to end-user consumption. For the purpose of maintaining a consistent and secure supply of LPG as well as detecting potential to enhance productivity and cut costs, it is crucial to comprehend its distribution network and all the stages associated to it.

The seven steps of the LPG supply chain are: (Elgas, 2023)

- Production
- Upstream transportation
- Refining and storage
- Downstream transportation
- Bottling and storage
- Distribution
- End users

Each stage of the process will be examined in this research.

3.1.1 PRODUCTION, UPSTREAM TRANSPORTATION AND REFINING AND STORAGE

The first step of the process is the production. In order to do so the extraction of LPG from oil and gas wells takes place in this stage. (Fanchi & Christiansen, 2016)

The majority of the LPG produced worldwide (60%) comes from gas processing. The remaining 40% of the production of LPG at a global level comes from oil refining. (WLPGA, s.f.)

Upstream, midstream, and downstream are the three segments that constitute the gas and oil industry. Although the midstream segment can be incorporated in the downstream sector for the scenarios of two-sector systems. The subsurface resource, its surface extraction and the fundamental infrastructure at the well site are all included in the upstream sector. (Fanchi & Christiansen, 2016)

The upstream transportation consists of mass quantities being transported to the following stage, the refining one, in which the LPG out will be obtained from the raw materials.

It is in the refining and storage step when the LPG its obtained from the raw products: processed gas or refined oil.

As previously stated, gas processing is the mayor source for LPG at a global level, producing around 60% of the total output. Gas wells are typically “wet wells”, from which natural gas is obtained. Other Natural Gas Liquids (NGLs) can make up to 10% of the volume of natural gas as it is extracted from the ground. Propane, isobutane, and butane, generally known as LPG, are a few of these. Certain NGLs, such as propane and butane, are removed from the unprocessed gas stream before natural gas is commercialized.

LPG is manufactured at an oil refinery during different steps of the process, such as atmospheric distillation, reforming, cracking, and others. Between 1 and 4% of the initial crude oil will be reflected by the amount of LPG obtained. Some factors that have an effect on the amount of LPG produced during the process of oil refining are the kind of crude oil, the level of refinery sophistication and the market value of propane and butane relative to other oil products that might be obtained during the process.

For those cases where the LPG is imported the storage aspect of this stage is duplicated. It is present in the origin country, in order to store the output of the refining facility. Moreover, storage facilities are also included in the importing country, the one that has purchased the LPG, where it is stored in large-scale storage facilities ready to be transferred to hubs or regional center where the filling usually takes place.

3.1.2 DOWNSTREAM TRANSPORTATION

The most common way of transporting gas is via pipelines, mainly for large-scale operations. Using pipelines, LPG can be transported long distances in a cost-effective manner and being efficient. Nevertheless, the investment needed in order to use pipelines is a major one and it also entails maintenance. Moreover, LPG might also be transported using ships to carry it through seas, oceans and sometimes rivers. Furthermore, transportation via rail, using specialized railcars, is another method of transportation used, especially convenient for shorter distances. Lastly, in some scenarios the best transportation alternative is using trucks, since roads are more easily available in some countries. (enea consulting, 2020) (Emerson Process Management, 2015)

To illustrate this point, Figure 1 provides a visual representation of the cost in EUR per ton per kilometre for transporting, in this instance, CO2. The comparison is drawn between pipeline transportation and marine transport via boats. Notably, the data reveals that the economic viability of pipeline transportation becomes evident for substantial quantities, exceeding 500 tons of CO2 in the given example. This scenario is akin to situations when pipelines are juxtaposed with alternative means of transportation such as trains and trucks. The rationale behind this similarity lies in the substantial initial investment required for establishing a pipeline and the considerable volume it must transport to render a more cost-effective outcome. In essence, the economics of scale play a pivotal role in making pipeline transportation economically advantageous GlobalCCSInstitute (2020).

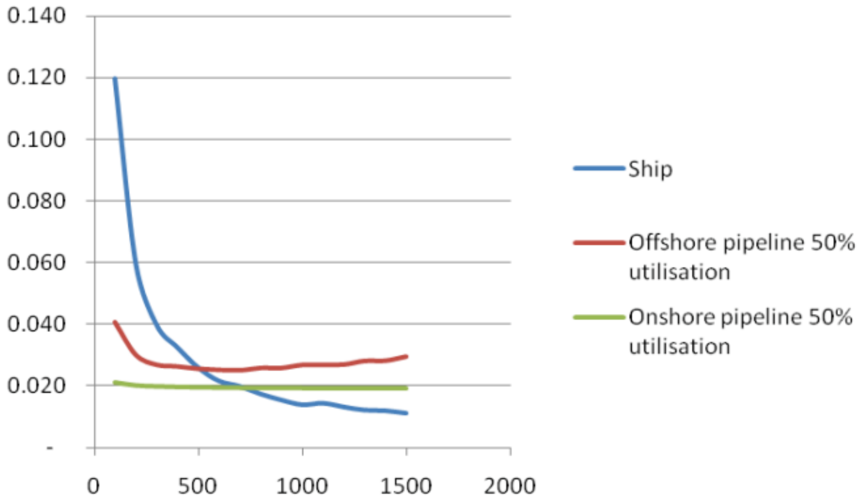


Figure 1. Cost expressed as EUR/km-tonne transported, for pipelines and ship transportation of CO2. Source: GlobalCCSInstitute (2020).

3.1.3 BOTTLING AND STORAGE

The LPG is either used to fill LPG cylinders or is kept in bulk LPG depots once it has been delivered downstream to a storage facility. This step guarantees that end users have access to LPG when they need it, which is essential to the supply chain.

Regarding the size of the bottling stations, to reduce filling expenses while enhancing safety, it is advised to target for a minimum filling plant size of at least 25KT/year. The suggested solution, when the region's demand is less than 10-15 KT/year, is to have a cylinder depot supplied by big, palletized trucks from the closest filling plant. In order to minimize filling expenses, administration costs, maintenance staff and machine costs, safety personnel and machinery costs, as well as filling costs, the filling plant should be situated as close to the retail location as possible without endangering the public. (GLPGP, 2020, Rwanda National LPG Master Plan).

In places that either use mass flow metering systems for dispensing the liquid or simple scales to account for the bulk by weight, filling small LPG cylinders is still a manual process. To conduct duties like filling and transporting cylinders, as well as testing reusable cylinders and plant systems, these filling/bottling areas frequently need a large number of employees—up to 50—to be present. Even slight gas leaks during these procedures have the potential to set things on fire or explode.

3.1.4 DISTRIBUTION

In the LPG supply chain, the transportation of LPG can be carried out through two primary methods: cylinders and bulk. LPG can be transported virtually anywhere using these modes of transportation NFCC, n.d.).

For the transportation of LPG in cylinders, trucks play a crucial role. After the bottling process at the LPG bottling site, trucks are responsible for transporting the filled cylinders to retailers, as well as directly to private and professional customers. These trucks ensure that the LPG cylinders reach their intended destinations, enabling widespread availability and accessibility of LPG for various end users. (Prithvirajan, et al., 2022)

In addition to cylinder transportation, small bulk trucks also play a significant role in the distribution of LPG. These trucks are specifically designed to transport LPG in bulk quantities from storage centers to different consumers. The storage centers serve as central hubs where LPG is stored before being distributed to various locations. The small bulk trucks then transport the LPG to consumers such as residential households, commercial establishments, and industrial facilities. (García López, 2017)

The use of trucks for LPG transportation provides flexibility and efficiency in reaching diverse customer segments. Whether it is delivering cylinders to retailers and individual customers or distributing bulk quantities of LPG to larger consumers, the transportation infrastructure ensures a seamless flow of LPG throughout the supply chain.

3.1.5 END USERS

In the LPG supply chain, ensuring easy availability of LPG to end users is essential. To cater to the diverse needs of customers, LPG is made easily accessible through various sales points and purchasing options.

For customers who require smaller quantities of LPG, cylinder sales points play a crucial role. These sales points can include commercial stores, service stations, and other retail outlets strategically located in close proximity to residential areas, commercial hubs, and public spaces. Customers can conveniently purchase LPG cylinders from these sales points to meet their domestic or small-scale commercial needs. The availability of LPG cylinders at these sales points ensures that customers have easy access to a reliable and convenient fuel source for their cooking and heating requirements.

On the other hand, customers with larger volume demands have the option to purchase LPG in bulk. Bulk LPG is typically purchased by commercial and industrial consumers who require a higher quantity of LPG for their operations. These customers may include businesses in the health sector, manufacturing industries, or large-scale cooking facilities such as hotels, restaurants, and catering services. Bulk LPG purchases allow these customers to have a consistent and ample supply of LPG to meet their specific usage requirements.

3.2 RWANDA'S CASE PARTICULARITIES

Rwanda, a small and landlocked country in Africa, is characterized by its hilly and fertile terrain. With a population exceeding 13 million people as of 2022, Rwanda shares borders with the Democratic Republic of Congo, Tanzania, Uganda, and Burundi (*Overview*, n.d.)

Covering an area of 26,338 square kilometers, Rwanda is a country characterized by its diverse physical features. The land is predominantly hilly, but it also encompasses swamps and expansive mountainous areas. The high altitude of Rwanda, averaging 1,700 meters in the central plateau uplands, contributes to its tropical highland climate. With the sun shining nearly all year round, the country enjoys a pleasant and temperate climate throughout the seasons. Regardless of the time of year, the average daily temperature hovers around 24°C. Nighttime temperatures tend to range around 10°C, while daytime temperatures can reach up to 34°C. Rwanda experiences two distinct wet seasons and two dry seasons, providing a rhythm to its climate patterns. (*East Africa Living Encyclopedia*, n.d.)

Rwanda, a country divided into five provinces, each with its own unique characteristics and contributions to the nation's development. The provinces, as shown in Figure 2, are the Northern Province, Western Province, Southern Province, Eastern Province, and the City of Kigali, which serves as both the capital and largest city of Rwanda.

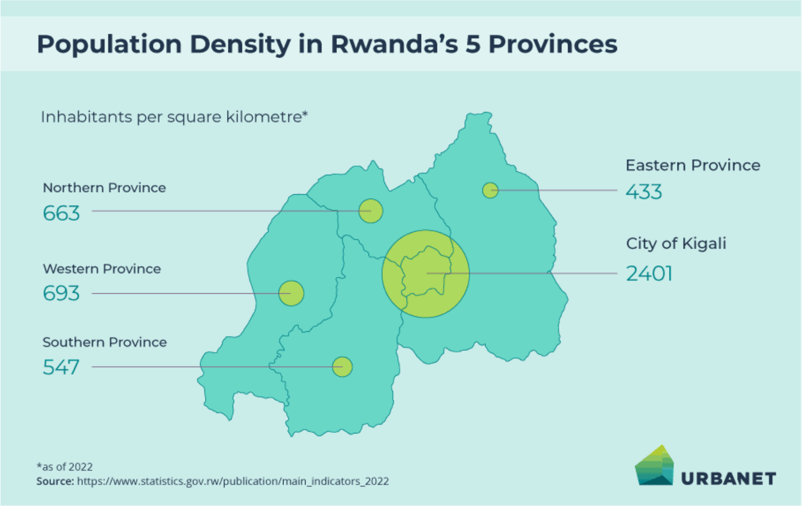
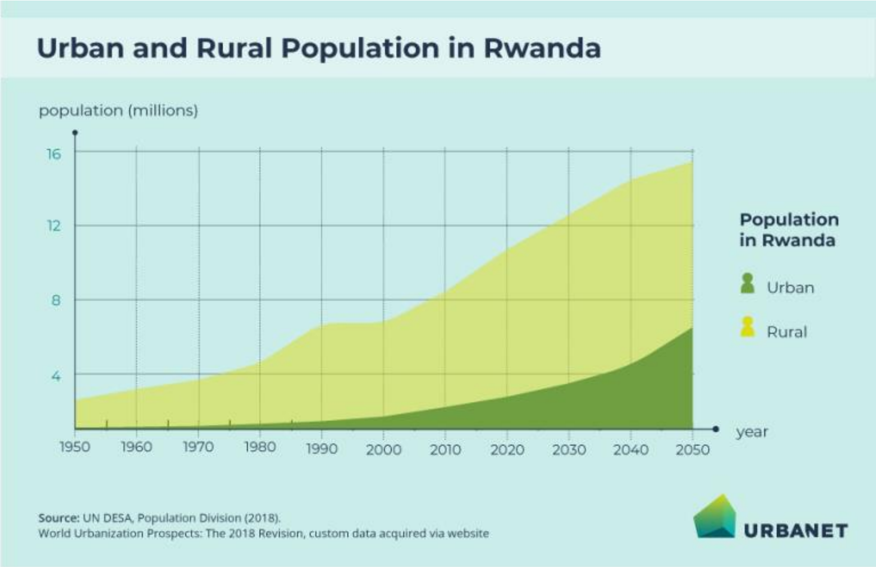


Figure 2. Map of Rwanda's Provinces and Population. Source: Urbanet (2023)

Kigali, located on Rwanda's central plateau, serves as the administrative, political, and commercial center of the country, attracting a significant portion of Rwanda's population. The graphic representation shown in Figure 3 highlights the concentration of people in urban areas, with Kigali being the most densely populated. The capital city is home to approximately 2,401 people per square kilometer. In contrast, the other provinces exhibit a relatively lower population density compared to the capital. This suggests a higher prevalence of rural settlements and agricultural activities in these regions. (Urbanet, 2023)



Source: UN DESA, Population Division (2018). World Urbanization Prospects: The 2018 Revision, custom data acquired via website

Figure 3. Urban and Rural Population Distribution in Rwanda. Source: Urbanet (2023)

Rwanda, as a landlocked country, faces geographical challenges due to its distance from maritime ports, with the nearest port of Dar Es-Salaam located approximately 1400 km away. This geographical reality poses constraints on the country's trade and transportation capabilities. Lacking a direct link to regional railways and inland water transport, Rwanda heavily relies on road transportation for trade activities. Furthermore, the country's dependence on imported fuel for transportation adds to the logistical complexities. (Ntamwiza, 2020)

Recognizing the significance of a robust transport sector in driving economic growth, Rwanda considers transport infrastructure as a strategic sector for expanding its economic base beyond agriculture and into the secondary and tertiary sectors. Efforts are being made to enhance the transportation network and infrastructure to facilitate trade and promote economic development.

Ntamwiza (2020) reports that, currently, Rwanda's transport infrastructure primarily consists of road transportation, with a network spanning approximately 14,000 km. The road network serves as the main artery for domestic and international connectivity, facilitating the movement of goods and people within and across borders. Additionally, the country has one international airport and six aerodromes, catering to an average of 1.4

million passengers annually, enabling air travel and connectivity. In terms of water transport, Rwanda's options are limited to Lake Kivu, which provides some access to water transportation. However, further development and utilization of water transport infrastructure within the country are yet to be fully realized.

The Government of Rwanda (GoR) has been actively implementing economic development measures and enacting reforms in the financial and business sectors, leading to significant improvements in the country's business climate. This progress is evident in Rwanda's remarkable rise in the World Bank Doing Business Report, moving from 139th place in 2010 to 38th place in 2016 (World Bank Group, 2020). Additionally, Rwanda has achieved remarkable strides in electrification, with coverage expanding from 10% in 2010 to 66.8% in 2021 (Rwanda Energy Group, n.d.a)

In (Bisaga, 2022) it is stated that, at present, Rwanda has a total installed generation capacity of 235.6 MW, with 11% of this capacity being imported, while the remainder is domestically generated. Hydrological resources account for 50.6% of the domestically generated capacity, thermal sources contribute 43.3%, and solar energy represents 5% of the total capacity (Rwanda Energy Group, n.d.b). Nevertheless, despite progress in electrification, a significant portion of the population, approximately 98%, still relies on traditional and polluting fuels like firewood, charcoal, and other biomass for cooking purposes. Surprisingly, none of the Rwandan households currently utilize electricity as their primary cooking fuel. Considering the compatibility of traditional Rwandan cuisine with electric cooking appliances, such as Electric Pressure Cookers (EPCs) and rice cookers, there exists substantial potential to transition households towards incorporating electric cooking in the future fuel mix.

Efforts are underway to explore and promote the adoption of electric cooking appliances as a cleaner and more sustainable alternative to traditional cooking methods. By encouraging the use of electric cooking appliances and gradually shifting away from polluting fuels, Rwanda aims to improve the overall well-being of its population, enhance environmental sustainability, and reduce indoor air pollution associated with traditional cooking practices.

(GLPGP, 2020) details that Rwanda's National Strategy for Transformation (NST-1) of 2017 established a specific target to address the issue of biomass cooking among the population. The objective was to reduce the percentage of Rwandans relying on biomass as their primary cooking fuel from 83% in 2017 to 42% by 2024. This ambitious target was driven by several key motivations. Firstly, there was a pressing need to alleviate the pressure on forests caused by extensive biomass consumption. Rwanda recognizes the importance of its forest ecosystems for biodiversity, climate regulation, and ecosystem services. By reducing the reliance on biomass, the country aimed to promote sustainable forest management and conservation. Secondly, achieving Sustainable Development Goal (SDG) 7, which focuses on ensuring universal access to clean and modern energy, was a critical priority. Access to clean energy sources is fundamental for improving the overall well-being of the population and supporting sustainable development. By transitioning away from biomass towards cleaner and more efficient energy sources, Rwanda aimed to make significant progress towards achieving SDG 7. Lastly, improving the health and quality of life for the people of Rwanda was a paramount concern. Biomass cooking, such as using firewood or charcoal, often leads to indoor air pollution, which can have severe health implications, particularly for women and children who spend significant time near cooking fires. By promoting the adoption of cleaner energy sources, Rwanda sought to mitigate these health risks and enhance the overall living conditions of its citizens.

Figure 4 shows the prevailing cooking fuel choices in Rwanda, highlighting the significant reliance on firewood as the dominant fuel source. This is particularly evident in rural areas, where a staggering 91.1% of households rely on firewood for cooking. Interestingly, among households using firewood, one-third reported gathering it for free, indicating a reliance on local resources for fuel procurement. In urban areas, charcoal emerges as the predominant cooking fuel. This holds true for the capital city of Kigali, where 76.9% of households rely on charcoal for cooking. Similarly, in other urban areas across the country, 44.5% of households use charcoal as their primary cooking fuel. The widespread use of charcoal in urban settings signifies its accessibility and convenience as a fuel source. These findings highlight the disparities in cooking fuel preferences between rural and urban areas in Rwanda. While firewood remains the primary choice in rural communities, urban areas have witnessed a significant shift towards charcoal as a cooking fuel. (Woolley, et al., 2022).

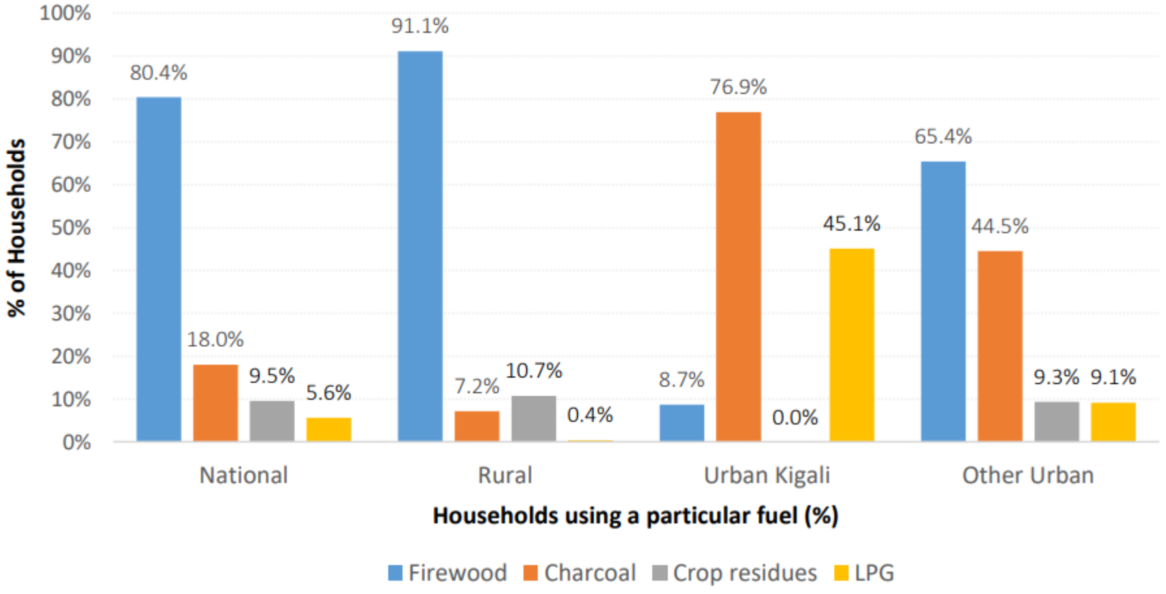


Figure 4. Rwanda's house cooking fuel used in 2020. Source: GLPGP (2020).

(GLPGP, 2020) also states that, over the years, there has been a notable rise in the adoption of LPG as a cooking fuel in Rwanda. Nationally, the usage of LPG for cooking has increased from 2.4% in 2016 to 5.6% in 2020, indicating a growing trend towards its utilization. Within the City of Kigali, the capital and largest urban center, the consumption of LPG has experienced a significant surge. In 2016, LPG usage stood at 7.4%, which then soared to 45.1% in 2020. This remarkable increase demonstrates the city's substantial shift towards LPG as a preferred cooking fuel. In fact, urban Kigali is the primary hub for LPG consumption in the country, with 45.1% of households relying on LPG for cooking. This urban usage accounts for an impressive 76.2% of the total national household LPG consumption. These statistics illustrate the growing popularity and acceptance of LPG as an alternative cooking fuel, particularly in urban areas such as Kigali. This transition to LPG usage contributes to Rwanda's efforts in promoting cleaner energy sources and offers several advantages, including cleaner burning, convenience, and reduced environmental impact compared to traditional fuels like firewood and charcoal., improving air quality, and enhancing the overall well-being of its population.

3.3 MODEL REQUIREMENTS

In the context of LPG distribution, understanding the cost implications of infrastructure and decision-making is of significant importance. A cost model serves as a valuable tool to evaluate and determine how various factors influence the overall costs involved in the distribution process. This section aims to present a comprehensive analysis of the requirements of a cost model designed to study the cost dynamics in LPG distribution networks. Specifically, the model focuses on assessing the effects of infrastructure and transportation investments and decision-making by the central planner. By providing key insights and disaggregated information, the cost model assists in making informed decisions and understanding cost structures in the distribution network.

The primary objective of the cost model is to delve into the intricate relationships between infrastructure and transportation investments and decision-making processes in the context of LPG distribution. Understanding the impact of infrastructure and transportation on costs is crucial as it enables the central planner to make informed choices.

The cost model provides a comprehensive evaluation of the total cost associated with LPG distribution. It takes into account various cost components, including infrastructure investments, vehicle operations or maintenance. When aggregating these costs, the model offers a holistic view of the financial implications of the distribution system. This information is valuable for budgeting, financial planning, and cost control measures, enabling the central planner to make data-driven decisions to optimize overall costs. In addition to assessing the total cost, the cost model also disaggregates the costs associated with different components of the distribution system. Since the model breaks down costs into specific categories, such as transportation, importation, warehousing, and bottle filling expenses, it provides a detailed understanding of the cost structure. This granularity allows the central planner to identify cost drivers, allocate resources effectively, and prioritize areas for cost reduction or optimization efforts.

To facilitate effective cost management and planning, the cost model differentiates between fixed costs and variable costs influenced by factors such as vehicle numbers and LPG demand. Through the precise identification and quantification of fixed and variable costs, the cost model empowers the central planner to evaluate the ramifications of fluctuations in variables and make well-informed decisions pertaining to fleet size, capacity utilization, and resource allocation.

One of the requirements of the cost model is to accurately estimate the number of cylinders needed for LPG distribution. By considering factors such as demand, losses in the different process and refill cycles. This information helps optimize logistical operations and minimize the costs associated with cylinder procurement, maintenance, and distribution.

Moreover, since understanding fuel consumption patterns is critical for assessing the efficiency of the distribution system. The cost model captures relevant data on fuel consumption, considering variables such as vehicle types or distances travelled. By analyzing fuel consumption patterns, the model enables the central planner to identify opportunities for fuel optimization.

Finally, the cost model serves an additional crucial purpose of providing comprehensive information and analysis pertaining to the impact of price changes. In an ever-evolving energy market, where fuel prices can exhibit significant volatility, understanding the implications of these fluctuations becomes paramount. Thanks to simulating and analyzing the effects of fuel price fluctuations on the cost of LPG distribution, the model enables decision-makers to gauge the potential financial impact on the supply chain. Furthermore, the cost model also facilitates a detailed examination of the cost implications arising from changes in the cost of importing LPG within the region.

3.4 MODELING ASSUMPTIONS

The cost model for the LPG supply chain plays a vital role in assisting central planners in making informed decisions regarding the efficient allocation of resources and optimizing cost-effectiveness. However, to create a workable and practical model, certain simplifications need to be made. This section aims to discuss and analyze the simplifications incorporated into the cost model for the LPG supply chain in Rwanda.

3.4.1 EXCLUSION OF GEO-REFERENCIATION OF ROADS

In the cost model for the LPG supply chain, it is important to acknowledge the simplification made regarding the exclusion of geo-referenciation of roads. This decision was made considering factors such as the complexity of data collection, limited availability of comprehensive road network data, and the scope of the project. While the accurate mapping and analysis of road networks could provide valuable insights into transportation distances and route optimization, it was deemed impractical for the current cost model.

3.4.2 SIMPLIFIED DISTANCE ESTIMATIONS

Distance calculations in the cost model are simplified, primarily considering round trips or radial routes. This approach allows for a reasonable approximation of transportation distances while considering the specific characteristics of the LPG supply chain in Rwanda.

3.4.3 CONSTANT DEMAND ASSUMPTIONS

One of the notable simplifications implemented in the cost model pertains to the assumption of a constant demand for LPG. Although this assumption may overlook the inherent variability in actual demand patterns, it offers a practical and sufficiently accurate approximation for planning purposes. It is important to note that 12-kg cylinder LPG consumption by the average household in Rwanda typically spans approximately one month, making the assumption of constant demand a reasonable approximation.

3.4.4 ROAD TRANSPORTATION FOCUS

Due to the geographical challenges faced by Rwanda as a landlocked country, previously explained in Rwanda’s Case particularities section, the cost model implemented for the LPG supply chain focuses exclusively on road transportation. This simplification is a direct response to the country's distance from maritime ports, with the nearest port of Dar Es-Salaam situated approximately 1400 km away. Rwanda's landlocked status and limited access to ports pose significant constraints on its trade and transportation capabilities. In line with these geographical realities, Rwanda lacks direct links to regional railways and inland water transport, further reinforcing the reliance on road transportation for trade activities. Furthermore, the country's reliance on imported fuel for transportation amplifies the logistical complexities faced by the LPG supply chain. With limited access to alternative modes of transportation such as rail or waterways, road transport becomes the primary means of importing and distributing petroleum derivatives, including LPG. By focusing exclusively on road transportation, the cost model accounts for the existing infrastructure and logistical requirements of the LPG market in Rwanda. This simplification enables a more targeted analysis of the costs and operational considerations associated with road-based distribution, providing insights, and informing decision-making for the central planner.

3.4.5 EXCLUSION OF LAST-MILE DISTRIBUTION COSTS

The cost model does not consider the last-mile distribution costs, which are typically handled by local distributors and can give rise to various business models. This simplification is made from the perspective of a central planner, aiming to focus on higher-level decision-making. However, it is important to note that proximity to distribution points is crucial for accessibility and market penetration.

The cost model implemented for the LPG supply chain in Rwanda intentionally excludes the consideration of last-mile distribution costs. This decision stems from the perspective of a central planner, where the primary focus is on higher-level decision-making rather than delving into the intricacies of local distribution operations, as shown in Figure 5

(GLPGP, 2020). Although the cost model does not directly account for last-mile distribution costs, it is essential to recognize the significance of proximity to distribution points in ensuring accessibility and market penetration. (Kumar et al., 2018) The accessibility of LPG to end consumers relies heavily on the presence of local distributors who handle the final stage of delivery to households and businesses. These local distributors often adopt diverse business models, ranging from direct sales to neighborhood shops or delivery services. While the cost model may not delve into the specific costs associated with last-mile distribution, it acknowledges the importance of proximity to distribution points in facilitating market penetration and ensuring the availability of LPG to consumers. The central planner must consider the strategic placement of distribution points and their proximity to target markets to maximize the reach and impact of the LPG supply chain.

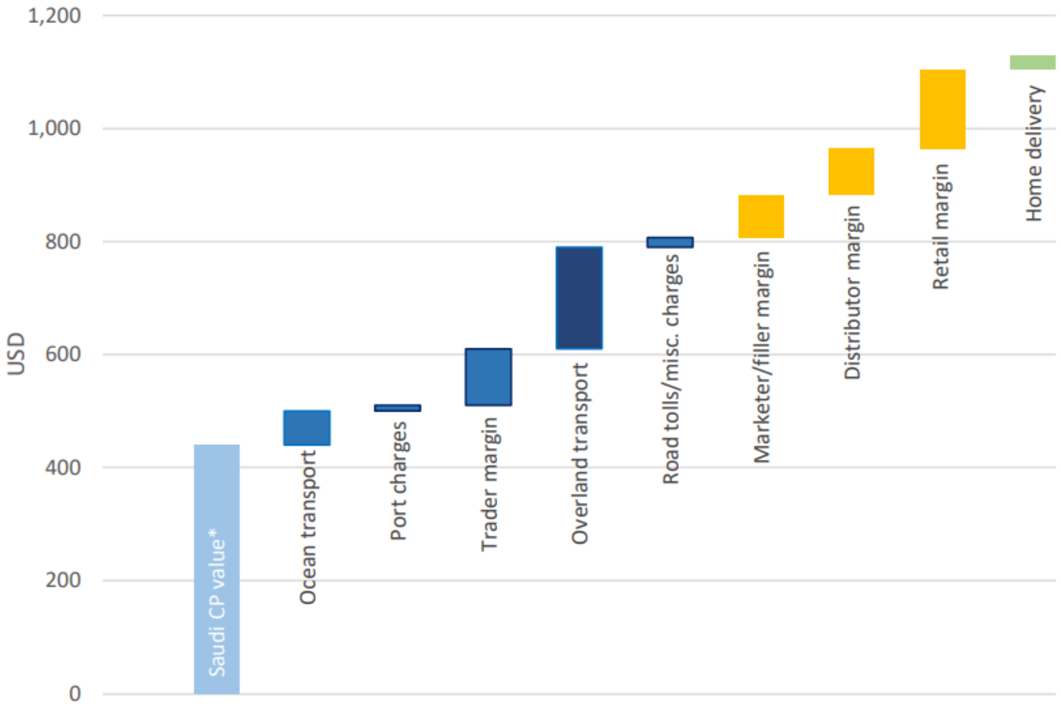


Figure 5. LPG price build-up per MT. Source: GLPGP (2020).

3.4.6 UNIFORM FUEL PRICES

Within the cost model for the LPG supply chain, a simplification is made by assuming uniform fuel prices throughout Rwanda. This means that the model does not take into account potential price variations across different regions within the country. By assuming uniform fuel prices nationwide, the cost model eliminates the complexity and potential data gaps that would arise from considering price differentials across regions. This simplification allows for a more straightforward and streamlined estimation of costs for the entire supply chain.

3.4.7 SUPPLY CHAIN STRUCTURE

While it is important to note that in general, countries may have their own oil refineries and domestic production capabilities, Rwanda's situation differs as it does not possess any oil refineries and relies heavily on imports to meet its LPG needs. Given this context, the supply chain model primarily revolves around key components such as LPG Depots, bottling stations, and warehouses. These elements form the backbone of the distribution system, facilitating the storage, processing, and efficient flow of LPG throughout the market.

3.4.8 RESIDUAL VALUE OF TRANSPORTATION VEHICLES AND INFRASTRUCTURE

In order to streamline the calculations and enhance the clarity of the model an assumption regarding the residual value of transportation vehicles and infrastructure has been made. Specifically, a null residual value for all transportation vehicles and infrastructure components involved in the LPG supply chain has been supposed. This assumption is grounded in the aim of simplifying the financial calculations and ensuring a straightforward evaluation of costs associated with the transportation aspect of the supply chain. In reality, transportation vehicles and infrastructure components do possess a residual value at the end of their useful lives. However, for the purposes of the model, they have been disregarded to avoid introducing an additional layer of complexity to the calculations.

3.5 PARAMETERS ESTIMATION

The accurate estimation of input data values is a crucial aspect in developing a robust cost model for the LPG supply chain. In this section, the focus is on the parameter estimation process, which involves determining the values of various input data categories such as LPG import, end-user prices, and infrastructure and transportation costs. These estimated values will serve as the foundation for executing the cost model and analyzing its outcomes.

Estimating input data values requires a meticulous approach, especially when dealing with limited available information and specific regional considerations. This study focuses on the case of Rwanda, a landlocked country in East Africa that relies heavily on imported petroleum derivatives for its LPG supply. Given the context and data availability, the aim of this section is to make reasonable assumptions and employ relevant information to estimate input data values that are as specific and accurate to the Rwandan context as possible.

The parameter estimation process involves a careful analysis of available data sources, including government reports, industry publications, market surveys, and relevant academic studies. These sources will be examined to gather information on LPG import volumes, pricing mechanisms, infrastructure costs, and transportation expenses. However, it is important to note that due to the nature of the study and the specific context of Rwanda, there may be instances where the required data is scarce or unavailable. In such cases, it will rely on reasonable assumptions based on industry standards, expert opinions, and comparable regional data.

In the following sections, the estimation process for each data category will be presented, highlighting the sources and assumptions used to derive the values, the base year for all parameters estimation is 2023. This parameter estimation section serves as a critical foundation for executing the subsequent cost model, enabling a comprehensive analysis of the LPG supply chain in Rwanda.

3.5.1 LPG IMPORTS

3.5.1.1 Importation price

In order to evaluate the import prices of LPG in Rwanda, it is essential to consider the current exporters to the country, which are Tanzania and Kenya. The landed cost of LPG imports to Rwanda from Tanzania is approximately 807 USD per metric ton (TON), while imports from Kenya have a landed cost of around 765 USD per TON. (GLPGP, 2020)

To determine the appropriate import price for Rwanda, a decision must be made between these two values. Although the lower cost may initially appear more favorable, it is important to note that, as stated in (GLPG, 2020) Rwandan LPG marketers who possess their own bulk trucks have expressed a preference for importing from Tanzania. This preference is based on several factors, including the need to cross two countries when importing from Kenya, which can lead to additional logistical complexities and delays for the trucks in general.

Considering the feedback and preferences of the local LPG marketers, a balanced approach is warranted. Therefore, the mean value between the landed costs from Tanzania and Kenya will be used as the estimated import price for Rwanda's LPG. This approach takes into account the market dynamics and considerations raised by the industry stakeholders. By adopting this mean value, we aim to strike a reasonable balance between cost efficiency and logistical feasibility, ultimately reflecting the current import price conditions in Rwanda's LPG market.

Therefore, based on the available information and considering the input data for LPG imports in the cost model, the estimated price will be set at **786 USD per metric ton**.

3.5.1.2 Importation license

The importation license, issued by the Rwanda Utilities Regulatory Authority (RURA), permits the importation of LPG into the country. It is a crucial regulatory requirement that ensures the safe and efficient importation of LPG to meet the energy needs of the population. The estimation of the parameters related will be based on the information provided by RURA (2018)

In terms of costs there are two terms related to the license:

3.5.1.2.1 Application fee

The application fee for obtaining the LPG importation license is set at **100,000 RWF.**[1] This fee covers the administrative costs associated with processing the application and conducting the necessary evaluations and assessments. This application fee must be paid both if it is the first time applying for the license and if the application is being for a renewal of an already approved license.

3.5.1.2.2 License Fee

The license fee for both the initial application and subsequent renewals is **2,500,000 RWF**. This fee represents the cost of obtaining the importation license and maintaining its validity. The license fee covers the regulatory oversight and monitoring of LPG importation activities, ensuring compliance with safety standards and regulations.

Another significant term related to this license is its validity:

3.5.1.2.3 Validity

The LPG importation license is valid for a period of **5 years**. After the initial application, the license must be renewed every 5 years to continue importing LPG into Rwanda. The

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[1] RWF/USD = 0.00083 [Date: 08/21/2023]

renewal process involves submitting the necessary documents and paying the required fees again.

3.5.2 CYLINDERS

3.5.2.1 Turnover rate

The rotation rate or turnover rate of LPG cylinders represents the frequency at which cylinders are exchanged or replaced within a specific time period. It is a measure of the utilization and movement of cylinders in the LPG supply chain. A higher turnover rate indicates that cylinders are being used and replaced more frequently, reflecting increased demand and consumption of LPG. On the other hand, a lower turnover rate suggests slower cylinder usage and replacement, which may indicate lower demand or longer usage cycles.

In order to estimate the turnover rate of LPG cylinders in Rwanda, previous data and insights from reliable sources were examined. According to the findings obtained from (GLPGP, 2020), a reasonable assumption for the annual turnover rate of LPG cylinders can be made. It was observed that in urban areas, the turnover rate stands at approximately 2.70, indicating that LPG cylinders are replaced or exchanged around 2.70 times per year. Similarly, in rural areas, the estimated turnover rate is approximately 2.30, reflecting a slightly lower frequency of cylinder replacement or exchange compared to urban areas.

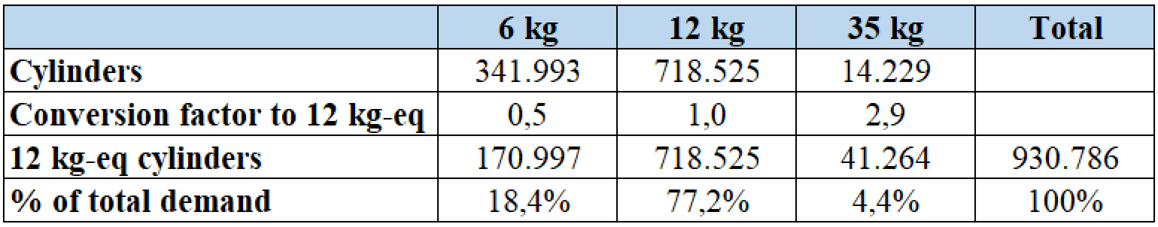
3.5.2.2 Sizes mix

When examining the parameters for estimating the cost of Rwanda's LPG supply chain, it is essential to consider various cylinder sizes incorporated within the model, aligning with Rwanda's LPG master plan (GLPGP, 2020). While the 12 kg cylinder remains the most prevalent choice, the plan recognizes the need to accommodate the diverse requirements of final consumers by considering additional sizes. In this regard, the cylinder sizes being assessed include **6 kg, 12 kg, and 35 kg**.

To accurately estimate the percentage of total demand covered by each cylinder type, the focus is directed towards the data provided by Rwanda's LPG master plan, specifically the targeted NST-1 (Rwanda's National Strategy for Transformation) scenario for the year 2024. This scenario serves as a key reference point for analyzing the projected demand and aligning it with the chosen cylinder sizes. A table is provided to showcase the estimated number of cylinders required for each size throughout the specified year.

Given that each cylinder type possesses a distinct capacity, it becomes necessary to employ a conversion factor tailored to the size of the respective cylinders. This conversion factor facilitates the estimation of the equivalent number of 12 kg cylinders, ensuring consistency in evaluating the demand coverage across different sizes. With the 12 kg-equivalent cylinders calculated, it becomes feasible to calculate the percentage of demand covered by each specific cylinder type.

It is important to highlight that the percentages presented in Table 1 are related to the demand covered by cylinders and should not be confused with the total number of cylinders required. For instance, to achieve the same demand coverage percentage, the quantity of 6 kg cylinders needed would be twice as high as the number of 12 kg cylinders. Therefore, this distinction emphasizes the significance of properly interpreting the figures provided, which specifically reflect the proportion of demand met by each cylinder size.



	6 kg	12 kg	35 kg	Total
Cylinders	341.993	718.525	14.229	
Conversion factor to 12 kg-eq	0,5	1,0	2,9	
12 kg-eq cylinders	170.997	718.525	41.264	930.786
% of total demand	18,4%	77,2%	4,4%	100%

Table 1. Cylinders size mix. Source: Own elaboration.

3.5.2.3 Empty cylinder acquisition price

The focus of this estimation lies on the three distinct cylinder sizes, as elucidated in the preceding section: 3kg, 12kg, and 45kg. To undertake this, an analysis of cylinder suppliers was conducted, encompassing the exploration of offerings provided by three distinct suppliers. To arrive at the estimation costs, a methodical approach was taken. The mean of the offers presented by each supplier was calculated for all three cylinder sizes. The culmination of this analysis yielded the following cost findings:

For the 3kg cylinder, the costs from the three suppliers were 9.48 USD, 8.4 USD, and 8.2 USD, respectively. The mean of these offers led to an estimated cost of approximately **8.70 USD**. In the case of the 12kg cylinder, the options provided costs of 10 USD, 13.5 USD, and 12.8 USD from the three suppliers. The resultant mean of these offers translated to an estimated cost of roughly **12.10 USD**. Finally, the 45kg cylinder displayed costs of 40 USD, 46.8 USD, and 45 USD across the three suppliers. By computing the mean of these offers, the estimated cost for the 45kg cylinder size amounted to approximately **43.90 USD.**

3.5.2.4 Requalification cost

LPG cylinder requalification is the practice of assessing and validating the safety and reliability of LPG (liquefied petroleum gas) cylinders after a designated period or usage. It is a vital procedure to guarantee the ongoing suitability and security of the cylinders. The requalification process involves comprehensive inspections and examinations to evaluate the structural soundness, resistance to leaks, and overall state of the cylinders. This process aids in identifying any potential flaws, damages, or signs of deterioration that could compromise their safety. Typically, the requalification process encompasses visual inspections, pressure tests, and occasionally supplementary non-destructive testing methods (Flatow, 2021).

The estimation of requalification costs in the cost model will be based on a report titled "Managing the Life Extension of LPG Cylinders," developed by the World LPG Association (WLPGA, 2016). This report examines the lifespan of LPG cylinders in 15 countries, providing valuable insights into the cost of requalification. Among the countries analyzed in the report, Brazil, India, and Taiwan were specifically assessed in terms of requalification costs per cylinder. The study revealed that the requalification cost per cylinder in Brazil is USD 7, in India is USD 1, and in Taiwan ranges between USD 12 and USD 15. To ensure a well-informed estimation, these cost values will be utilized.

As the requalification cost for Taiwan is presented as a range, with a mean value of USD 13.5, this value will be considered for the estimation. By calculating the arithmetic mean of USD 7, USD 1, and USD 13.5, for the study the estimated **requalification cost will be USD 7.17 per cylinder**. This estimation enables the cost model to account for requalification expenses accurately and support informed decision-making in the LPG supply chain analysis.

3.5.2.5 Requalification frequency

According to the requalification or revalidation regulation guidelines set by the Government of Rwanda, it is required that cylinders undergo **requalification every 10 years** (RURA, 2018). This means that after a period of 10 years, cylinders used for storing and transporting LPG need to be inspected and tested to ensure their continued safety and compliance with regulatory standards. The requalification process plays a crucial role in maintaining the integrity and safety of LPG cylinders throughout their lifespan, providing assurance to both industry stakeholders and end-users that the cylinders are fit for use.

3.5.2.6 Lifespan

An important factor to consider is the lifespan of the cylinders, as outlined in Rwanda's LPG Master Plan (GLPGP, 2020). According to the plan, a lifespan of **20 years** is anticipated for the cylinders used within the supply chain.

Taking into account this projected lifespan is crucial for accurately estimating the costs associated with cylinder acquisition, maintenance, and replacement. It allows for the incorporation of depreciation and lifecycle costs in the cost model.

This determination of a 20-year lifespan for the cylinders in Rwanda's LPG master plan (GLPGP, 2020) aligns both with industry standards and with regulatory measures implemented in various regions to ensure the safe utilization of LPG cylinders since it accounts for factors such as material durability, structural integrity, and performance reliability throughout a prolonged period of use, guaranteeing their sustained functionality and minimizing the risk of potential hazards.

3.5.3 TRANSPORTATION

3.5.3.1 Fuel price

It is important to note that while there are different types of fuels that can be used by vehicles, our analysis will specifically consider diesel fuel prices. This choice is based on the predominant use of diesel in trucks, as evidenced by data from the United States where 97% of the largest highway tractor-trailer size trucks and 75% smaller and medium-duty commercial trucks are powered by diesel. (*Diesel & the Trucking Industry | Diesel Technology Forum*, n.d.)

To estimate the diesel fuel price for the cost model, we will consider two factors. Firstly, we have the current diesel price of 1492 RWD per liter (*Rwanda Energy Prices | GlobalPetrolPrices.com*, n.d.). Additionally, the Rwandan government has implemented a diesel price cap of 1587 RWD per liter (RURA, 2022) that will also be taken account for potential future increases.

By taking the mean value between the current diesel price and the diesel price cap, we can arrive at an estimated **fuel price of 1550 RWD per liter**. This approach ensures that the fuel price estimation captures both the present market conditions and potential fluctuations in the future, providing a reasonable basis for the cost model's fuel cost calculations in the context of truck transportation in Rwanda.

3.5.3.2 Bulk transportation

This section focuses on a critical part of the LPG supply chain: bulk transportation. This is the stage where large amounts of LPG are moved from the depot to the bottling station in bulk quantities.

3.5.3.2.1 License for LPG Transportation in Bulk

In the LPG supply chain in Rwanda, the transportation of LPG in bulk or cylinders is a critical aspect that requires proper regulation and monitoring. The Rwanda Utilities Regulatory Authority (RURA) plays a vital role in ensuring the safe and efficient transportation of LPG within the country. RURA issues a License for LPG Transportation in Bulk or cylinders, which serves as a legal permit authorizing the transportation of LPG. It is important to note that this license requirement does not apply to consumers transporting a reasonable amount of LPG in their private vehicles.

In this section, the focus is on estimating the costs associated with obtaining and renewing the LPG bulk transportation license. This license is mandatory for both bulk transportation and transportation of LPG cylinders, and it will be referred to in subsequent sections of this study. The fees and validity period set by RURA (2018) will be consider to provide an estimation of parameters associated with this regulatory requirement.

To estimate the expenses related to the LPG bulk transportation license, we consider the following cost components:

Application Fee

The application fee for obtaining the LPG bulk transportation license is set at **50,000 RWF**. This fee covers the administrative costs associated with processing the application, conducting necessary evaluations, and ensuring compliance with transportation regulations. This application fee must be paid both if it is the first time applying for the license and if the application is being for a renewal of an already approved license.

License Fee

The license fee for both the initial application and subsequent renewals is **500,000 RWF**. This fee represents the cost of obtaining the transportation license and maintaining its validity. It covers the regulatory oversight and monitoring of LPG transportation activities, ensuring compliance with safety standards, and promoting the safe transportation of LPG within Rwanda.

Finally, there is one more relevant parameter associated with this license, its validity:

Validity

The LPG bulk transportation license is valid for a period of **5 years**. After the initial application, the license must be renewed every 5 years to continue transporting LPG in bulk or cylinders. The renewal process involves submitting the required documents and paying the required fees again.

3.5.3.2.2 Cost of acquisition

In order to accurately estimate the parameters for the cost model of Rwanda's LPG supply chain, one crucial aspect to consider is the determination of the selling price or acquisition cost for bulk transportation vehicles. This estimation relies on valuable insights derived from the "Observatorio de Costes del Transporte de Mercancías por Carretera" (Cost Observatory of Road Freight Transport) report, which was elaborated by the Ministry of Transport, Mobility, and Urban Agenda of Spain (MITMA, 2018). Within this comprehensive study, a specific case examining the bulk transportation of LPG is presented, offering relevant data for our analysis.

According to the findings presented in the study, the selling price of the tractor head, based on the applicable tariff, is estimated to be EUR112,965.33. However, it is important to note that a 10% discount can be obtained, resulting in a reduced amount of EUR101,668.80. Similarly, the study estimates the selling price of the tanker semi-trailer to be EUR86,491.36, considering the prevailing tariff. However, taking advantage of a 5% discount opportunity, the remaining payment required for the semi-trailer would amount to EUR82,166.79. By summing up these figures, the total cost per unit for the bulk transportation vehicle can be calculated to be **EUR183,835.59.**

3.5.3.2.3 Lifetime

In the process of estimating the lifespan of LPG bulk trucks for the cost model of Rwanda's LPG supply chain, reference is made to industry standards and regulations. Specifically, the Department of Petroleum Resources (DPR) and the Standards Organization of Nigeria

(SON) have established guidelines pertaining to the longevity of LPG trailers, which are relevant in this context (allafrica, 2014).

Both regulatory bodies have agreed upon a lifespan range of 30 to 40 years for pressure vessels, including LPG trailers. These guidelines ensure compliance with safety standards and promote the secure operation of LPG transportation systems. Therefore, within the scope of the cost model, the mean value of this range, which is 35 years, is considered as the estimated lifespan for LPG bulk trucks.

3.5.3.2.4 VOM

Estimating the variable operation and maintenance (VOM) cost of an LPG bulk transportation vehicle requires careful analysis of available information. Firstly, considering Rwanda's LPG master plan, valuable insights regarding transportation costs can be found in its annexes. Although the comparison presented in the annexes focuses on European and Western African prices, it is important to note that Rwanda is not located in West Africa (GLPGP, 2020). However, due to the lack of more specific information and the acceptance of these assumptions within Rwanda's LPG master plan, they will be considered valid for the estimation. While acknowledging the geographical disparity, the utilization of the assumptions provided in the LPG master plan allows for a pragmatic approach in the absence of more specific data. However, it is important to continually seek updated and localized information in the future to refine and enhance the accuracy of the cost model.

Based on the data provided in the document, a reasonable estimation for the VOM of a bulk transportation vehicle can be set at **0.186 EUR/km**, excluding fuel consumed costs, since it will be calculated separately in the model to take into account other factors as fuel price variations. However, this estimation accounts for other factors such as tires, maintenance, and repairs costs.

3.5.3.2.5 FOM

Estimating the fixed operation and maintenance cost of an LPG bulk transportation vehicle entails examining relevant studies and analyses. In this case, a review commissioned by the World Bank (Teravaninthorn et al., 2019), on Africa's international corridors' transportation prices and costs, provides valuable insights. The study includes an analysis of different African corridors, including the Kampala-Kigali route, which connects the capitals of Uganda and Rwanda in East Africa.

The review emphasizes that some corridors exhibit higher levels of volatility, with variable costs representing a significant portion of the total transportation cost. However, it highlights that the Kampala-Kigali corridor predominantly consists of fixed costs. Specifically, the study concludes that the fixed costs account for 56% of the yearly total costs, while the variable costs make up the remaining 44%.

Based on this information, the cost model for Rwanda's LPG supply chain adopts a parameter for fixed costs derived from the study. The fixed costs are computed as **127% of the total variable costs** incurred for bulk transportation vehicles. This approach considers the relatively stable nature of the region where the Kampala-Kigali corridor is located, and that is valid for Rwanda’s case, where fixed costs play a more substantial role in the overall transportation expenses. By incorporating this parameter into the cost model, a more accurate estimation of the fixed operation and maintenance costs for LPG bulk transportation vehicles can be achieved. While this estimation is based on historical information and specific to the Kampala-Kigali corridor, it serves as a reasonable approximation within the absence of more current or localized data. Future research and data collection efforts should aim to enhance the accuracy of the fixed cost estimation specific to the LPG supply chain in Rwanda.

3.5.3.2.6 Fuel consumption

To estimate the fuel consumption of an LPG bulk transportation vehicle, the analysis draws upon valuable insights from the "Observatorio de Costes del Transporte de Mercancías por

Carretera" (Cost Observatory of Road Freight Transport) report (MITMA, 2018). This report, prepared by the Ministry of Transport, Mobility, and Urban Agenda of Spain in 2023, offers a comprehensive study that includes a specific case focused on the bulk transportation of LPG. Within this study, the fuel consumption of a standard truck utilized for the bulk transportation of LPG is examined, providing relevant data for our analysis. Although the study may not directly represent the conditions and context of Rwanda, it provides a valuable reference point for estimating fuel consumption within the absence of more localized data. As the LPG supply chain in Rwanda evolves, it is essential to continuously monitor, and update fuel consumption estimations based on actual operational data and local conditions. Based on the findings presented in the report, the fuel consumption rate of the studied standard truck is set at **34.5 liters per 100 kilometers**.

3.5.3.2.7 Capacity

The estimation of the capacity of LPG bulk transportation vehicles takes into consideration the information provided in the Rwanda master plan. The master plan emphasizes that the capacity of these trucks is subject to regulations governing the authorized axle load. As stated in the plan, the typical range for LPG capacity in bulk transportation trucks is between 20 and 28 metric tons and to simplify calculations the assumption made in the report is that the capacity for these vehicles is 24 ton (GLPGP, 2020).

For the purpose of the calculations and estimations in this analysis, it is consistent with the assumption made in the report that LPG bulk transportation trucks have a capacity of **24 ton**. This assumption aligns with the standard capacity considered in the master plan and ensures consistency throughout the modeling and analysis processes.

3.5.3.3 Primary transportation

This section focuses on the parameters related to primary transportation. This is the stage where the cylinders filled in the bottling station are transported from said station to a warehouse to be distributed from there.

3.5.3.3.1 License for LPG Transportation in cylinders

As part of the regulatory framework, the Rwanda Utilities Regulatory Authority (RURA) requires a License for LPG Transportation in bulk or cylinders. This license serves as a legal permit authorizing the transportation of LPG within the country (RURA, 2018). It is important to note that the same transportation license described previously for bulk transportation applies to primary transportation as well, as it involves transporting LPG in bulk quantities or in cylinders, so least detail will be included in this section. Therefore, the main parameters related to the license are:

Application Fee

The application fee for obtaining the license to transport LPG in cylinders is set at **50,000 RWF**. This application fee must be paid both if it is the first time applying for the license and if the application is being for a renewal of an already approved license.

License Fee

The license fee for both the initial application and subsequent renewals is **500,000 RWF**.

Validity

The LPG cylinders transportation license is valid for a period of **5 years**. After the initial application, the license must be renewed every 5 years.

3.5.3.3.2 Cost of acquisition

In estimating the acquisition price of LPG primary transportation vehicles, the analysis takes into account Rwanda's master plan, which provides valuable information on transport investment requirements. Specifically, the master plan includes tables that outline the costs associated with different truck types. Upon reviewing these tables, it becomes apparent that the cost estimation for acquiring one unit of primary transportation truck is set at USD170,200. This estimation is applicable for scenarios where a single truck is required in a given year. As the demand for additional trucks increases over subsequent years, the acquisition costs are proportionally adjusted accordingly (GLPGP, 2020).

Based on this information, the acquisition price for LPG primary transportation trucks in the cost model is estimated at **USD170,200**. This estimation serves as a benchmark for evaluating the capital investment required to procure the necessary fleet of primary transportation vehicles within the LPG supply chain in Rwanda.

3.5.3.3.3 Lifetime

For the estimation of the lifespan of LPG primary transportation vehicles, valuable insights are derived from TriState Truck Center, a reputable company specializing in class 8 trucks (tristatetruck, n.d.).

These trucks fall under the category of "heavy-duty" as defined by the Federal Highway Administration (FHWA). The FHWA employs a classification system that categorizes trucks into different groups based on their weight and intended use. The groups range from light-duty (1-2) to medium-duty (3-6) and finally, heavy-duty (7-8). One of the key criteria used to determine the classification of trucks is the gross vehicle weight rating (GVWR). The GVWR refers to the maximum permissible weight of a fully loaded truck, including the vehicle itself, cargo, passengers, and any additional equipment. In the case of class 8 trucks, the GVWR encompasses any weight above 33,000 pounds (14,969 kg) (Arrowtruck. (2022).

According to TriState Truck Center, the average expected lifespan for a typical semi-truck, which falls under the class 8 category, is approximately 15 years (Thorne, n.d.). This information serves as a reliable benchmark for estimating the lifespan of primary transportation vehicles within the LPG supply chain. Therefore, in the cost model for Rwanda's LPG supply chain, the estimated lifespan for LPG primary transportation vehicles is established at **15 years**.

3.5.3.3.4 VOM

Estimating the variable operation and maintenance cost (VOM) of an LPG primary transportation vehicle requires careful analysis of available information. Firstly, considering Rwanda's LPG master plan, valuable insights regarding transportation costs can be found in its annexes. Although the comparison presented in the annexes focuses on European and Western African prices, it is important to note that Rwanda is not located in West Africa (GLPGP, 2020). However, due to the lack of more specific information and the acceptance of these assumptions within Rwanda's LPG master plan, they will be considered valid for the estimation. While acknowledging the geographical disparity, the utilization of the assumptions provided in the LPG master plan allows for a pragmatic approach in the absence of more specific data. However, it is important to continually seek updated and localized information in the future to refine and enhance the accuracy of the cost model.

Based on the data provided in the document, a reasonable estimation for the VOM of a primary transportation vehicle can be set at **0,186 EUR/km**, same as for a bulk transportation vehicle, excluding fuel consumed costs, since it will be calculated separately in the model to take into account other factors as fuel price variations. However, this estimation accounts for other factors such as tires, maintenance, and repairs costs.

3.5.3.3.5 FOM

The same review commissioned by the World Bank (Teravaninthorn et al., 2019), on Africa's international corridors' transportation prices and costs, used for the bulk transportation segment can be applied in primary transportation research. Specifically, the study concludes that the fixed costs account for 56% of the yearly total costs, while the variable costs make up the remaining 44%. Based on this information, the cost model for Rwanda's LPG supply chain adopts a parameter for fixed costs derived from the study. The fixed costs are computed as **127% of the total variable costs** incurred for primary transportation vehicles, same as for bulk transportation vehicles, since the study does not differentiate between vehicles. This approach considers the relatively stable nature of the region where the Kampala-Kigali corridor is located, and that is valid for Rwanda's case, where fixed costs play a more substantial role in the overall transportation expenses. By incorporating this parameter into the cost model, a more accurate estimation of the fixed operation and maintenance costs for LPG bulk transportation vehicles can be achieved. While this estimation is based on historical information and specific to the Kampala-Kigali corridor, it serves as a reasonable approximation within the absence of more current or localized data. Future research and data collection efforts should aim to enhance the accuracy of the fixed cost estimation specific to the LPG supply chain in Rwanda.

3.5.3.3.6 Fuel consumption

To estimate the fuel consumption of LPG primary transportation vehicles, the comprehensive "Observatorio de Costes del Transporte de Mercancías por Carretera" (Cost Observatory of Road Freight Transport) report is references (MITMA, 2023). One of the cases analyzed in the report pertains to a specific type of vehicle, namely a 3-axle rigid truck for general cargo. This vehicle is characterized by a gross vehicle weight rating (GVWR) of 26.000 kg, which aligns with the definition of a class 8 vehicle mentioned earlier in the Lifetime section. As previously stated, class 8 vehicles are categorized as those with a GVWR exceeding 15,000 kg. Within this study, the fuel consumption of a standard truck used for LPG primary transportation is examined, providing relevant data for our analysis. While this study may not directly reflect Rwanda's conditions and context, it serves as a valuable point of reference for estimating fuel consumption in the absence of localized data. As Rwanda's LPG supply chain progresses, continuous monitoring and updates to fuel consumption estimations based on actual operational data and local conditions are essential. According to the report, the studied standard truck demonstrates a fuel consumption rate of **27,0 liters per 100 kilometers**, which serves as a significant parameter for our cost model's estimation.

3.5.3.3.7 Capacity

The estimation of the capacity for LPG primary transportation vehicles is informed by the Rwanda master plan (GLPGP, 2020). According to the plan, the capacity of primary transportation trucks is estimated to be 10 ton per trip, as they supply the entrepots from the associated filling plants. The equivalent of said capacity is **833 12 kg-eq cylinders.** This estimation will be maintained throughout the model.

3.5.3.4 Secondary transportation

This section focuses on the parameters associated to secondary transportation, which is the stage where the cylinders are being moved from the warehouses to the different demand clusters, usually the stores where they will be sold to the final consumers.

3.5.3.4.1 License for LPG Transportation in cylinders

As part of the regulatory framework, the Rwanda Utilities Regulatory Authority (RURA) requires a License for LPG Transportation in Bulk or cylinders. This license serves as a legal permit authorizing the transportation of LPG within the country (RURA, 2018). It is important to note that the same transportation license described previously for bulk and primary transportation applies to primary transportation as well, since it is valid for LPG transportation both in bulk quantities as well as in cylinders, so least detail will be included in this section. Therefore, the main parameters related to the license are:

Application Fee

The application fee for obtaining the license to transport LPG in cylinders is set at **50,000 RWF**. This application fee must be paid both if it is the first time applying for the license and if the application is being for a renewal of an already approved license.

License Fee

The license fee for both the initial application and subsequent renewals is **500,000 RWF**..

Validity

The LPG cylinders transportation license is valid for a period of **5 years**. After the initial application, the license must be renewed every 5 years.

3.5.3.4.2 Cost of acquisition

To accurately estimate the parameters for Rwanda's LPG supply chain cost model, it is also important to estimate the selling price or acquisition cost of secondary transportation vehicles. This estimation draws upon valuable insights from the "Observatorio de Costes del Transporte de Mercancías por Carretera" (Cost Observatory of Road Freight Transport) report, prepared by the Ministry of Transport, Mobility, and Urban Agenda of Spain (2023) (MITMA, 2023). One of the cases analyzed in the report pertains to a specific type of vehicle, namely a 2-axle rigid truck for distribution, that will be assumed similar to the ones required for secondary transportation. The study's findings reveal the estimated selling price of the tractor head, based on the applicable tariff, to be **EUR53,771.28**.

3.5.3.4.3 Lifetime

This estimation draws upon valuable insights from the "Observatorio de Costes del Transporte de Mercancías por Carretera" (Cost Observatory of Road Freight Transport) report, prepared by the Ministry of Transport, Mobility, and Urban Agenda of Spain (2023) (MITMA, 2023). One of the cases analyzed in the report pertains to a specific type of vehicle, namely a 2-axle rigid truck for distribution, that will be assumed similar to the ones required for secondary transportation. The study estimates its expected lifespan to be **10 years**.

3.5.3.4.4 VOM

The estimation of the variable costs for a secondary transportation vehicle draws upon valuable information from the "Observatorio de Costes del Transporte de Mercancías por Carretera" report (MITMA, 2023). Within this report, one of the cases analyzed focuses on a specific type of vehicle, specifically a 2-axle rigid truck utilized for distribution purposes, which can be assumed to be similar to those required for secondary transportation in our context.

According to the report's findings, the estimated variable costs for this type of vehicle, excluding fuel costs, are approximately **0.184 EUR per kilometer**. It is important to note that, in the cost model, fuel costs will be considered separately and calculated based on specific fuel consumption estimations. Therefore, the variable costs being estimated here solely encompass other operational expenses associated with the secondary transportation vehicle.

3.5.3.4.5 FOM

The same review commissioned by the World Bank (Teravaninthorn et al., 2019), on Africa's international corridors' transportation prices and costs, used for the bulk transportation segment can be applied in primary transportation research. Specifically, the study concludes that the fixed costs account for 56% of the yearly total costs, while the variable costs make up the remaining 44%. In light of this information, the cost model for Rwanda's LPG supply chain adopts a parameter for fixed costs derived from the study. The fixed costs are calculated as 127% of the total variable costs incurred for secondary transportation vehicles, following the same approach as for bulk and primary transportation vehicles. It is important to note that the study does not differentiate between vehicle types. This methodology takes into account the relatively stable nature of the region where the Kampala-Kigali corridor is located and assumes its applicability to Rwanda's case, where fixed costs play a significant role in overall transportation expenses. By incorporating this parameter into the cost model, a more accurate estimation of the fixed operation and maintenance costs for LPG primary transportation vehicles can be achieved.

3.5.3.4.6 Fuel consumption

For estimating the fuel consumption of LPG secondary transportation vehicles, the analysis refers to the informative "Observatorio de Costes del Transporte de Mercancías por Carretera" report (MITMA, 2023). This report, prepared by the Ministry of Transport, Mobility, and Urban Agenda of Spain in 2023, presents a comprehensive study that includes a specific case study focusing on a 2-axle rigid truck for distribution, that will be assumed similar to the ones required for secondary transportation.

Within this study, the fuel consumption of a standard truck of this kind is examined, providing relevant data for our analysis. While acknowledging that the study may not perfectly reflect Rwanda's conditions and context, it serves as a valuable point of reference for estimating fuel consumption when localized data is unavailable. As the LPG supply chain in Rwanda progresses, it is crucial to continuously monitor and update fuel consumption estimations based on real operational data and local conditions. According to the report's findings, the fuel consumption rate of the studied standard truck is set at **19.0 liters per 100 kilometers**.

3.5.3.4.7 Capacity

In estimating the capacity of LPG secondary transportation vehicles, the Rwanda master plan provides valuable insights (GLPGP, 2020). According to the master plan, the distribution of LPG can be accomplished using various vehicles, ranging from small trucks to cars and even motorcycles.

The master plan simplifies the capacity estimation by categorizing the secondary vehicles into four different sizes. These sizes correspond to the number of 12 kg-eq cylinders that each vehicle can carry per trip. The options provided are 140, 210, 315, or 420 cylinders per trip. However, for the purpose of this study, the focus will be on just one type of secondary vehicle.

To streamline the analysis, only one type of secondary vehicle will be considered in this study. In order to compute the mean capacity across the available options, the values of 140, 210, 315, and 420 cylinders will be taken into account. By averaging these values, we arrive at an estimated capacity of **270 cylinders per truck**.

3.5.4 INFRASTRUCTURE

3.5.4.1 LPG Depot

An LPG depot is a specialized storage facility where imported or produced liquefied petroleum gas (LPG) is stored before its distribution to bottling plants for further processing. Functioning as a strategic hub in the LPG supply chain, the depot serves as a temporary repository for large quantities of LPG. This stored LPG is subsequently transported to bottling plants, where it is meticulously filled into cylinders for consumer use.

3.5.4.1.1 LPG bulk storage facility installation license

In order to ensure the safe storage and handling of LPG in Rwanda, the installation of bulk storage facilities requires a specific license issued by the Rwanda Utilities Regulatory Authority (RURA). This license, known as the License for LPG Plant or Bulk Storage Facility Installation, is a legal permit that authorizes the establishment and operation of LPG storage facilities. It plays a crucial role in maintaining the integrity and safety of LPG storage infrastructure (RURA, 2018).

License fee

The only cost component for obtaining the LPG bulk storage facility installation license is the license fee. Based on the information available, the license fee is set at **1,000,000 RWF**. This fee covers the regulatory oversight and monitoring of the installation and operation of bulk storage facilities, ensuring compliance with safety standards, and promoting the safe handling of LPG in Rwanda.

3.5.4.1.2 LPG bulk storage facility operations license

To ensure the safe and compliant operation of LPG bulk storage facilities in Rwanda, the Rwanda Utilities Regulatory Authority (RURA) issues a specific license known as the License for LPG Plant or Bulk Storage Facility Operations. This license serves as a legal permit that authorizes the ongoing operation and management of LPG storage facilities. (RURA, 2018)

The cost components for obtaining and renewing the LPG bulk storage facility operations license include the application fee and the license fee.

Application Fee

The application fee for the initial license application is set at **200,000 RWF**. This fee covers the administrative costs associated with processing the application, conducting necessary evaluations, and ensuring compliance with operational and safety regulations. This application fee must be paid both if it is the first time applying for the license and if the application is being for a renewal of an already approved license.

License Fee

The license fee, applicable for both the initial application and subsequent renewals, is set at **5,000,000 RWF**. This fee represents the cost of obtaining and maintaining the LPG bulk storage facility operations license. It covers the regulatory oversight, monitoring, and inspection activities required to ensure the safe and compliant operation of the storage facility. The license fee also contributes to the ongoing surveillance and enforcement of operational and safety standards for LPG storage operations.

Validity

The LPG bulk storage facility operations license is valid for a period of **3 years**. After the initial application, the license must be renewed every 3 years to continue operating the bulk storage facility. The renewal process involves submitting the necessary documents and paying the required fees again.

3.5.4.2 Bottling station

A bottling station is a key component within the LPG supply chain responsible for receiving bulk shipments of liquefied petroleum gas (LPG) from depots. At this facility, the received LPG is utilized to fill individual cylinders, which are then destined for distribution to end consumers.

3.5.4.2.1 LPG plant installation license

Due to the overlapping nature of licenses, the License for LPG Plant Installation is the same as the one required for the installation of LPG bulk storage facilities (RURA, 2018). Since it has been previously explained, least detail will be included in this section.

License fee

The only cost component for obtaining the LPG bulk storage facility installation license is the license fee. Based on the information available, the license fee is set at **1,000,000 RWF**.

3.5.4.2.2 LPG plant operations license

Given the overlapping nature of licenses, it is noteworthy to mention that the License for LPG Plant operations is synonymous with the license necessary for the operations of LPG bulk storage facilities (RURA, 2018). As detailed information on this topic has been previously provided, this section will present a condensed summary of the key parameters associated with the license.

Application Fee

The application fee for the initial license application is set at **200,000 RWF**. This application fee must be paid both if it is the first time applying for the license and if the application is being for a renewal of an already approved license.

License Fee

The license fee, applicable for both the initial application and subsequent renewals, is set at **5,000,000 RWF**.

Validity

The LPG bulk storage facility operations license is valid for a period of **3 years**. After the initial application, the license must be renewed.

3.5.4.2.3 Lifetime

The estimation of the lifespan for LPG bottling stations is informed by the assumptions presented in Rwanda's LPG master plan (GLPGP, 2020). When formulating industry business cases, the plan takes into account various factors that impact firm and sector economics. One key assumption made in line with industry conventions is that a depreciation period of 15 years is appropriate for bottling plants.

Given that the primary purpose of this lifespan estimation within the model is to evaluate the economic aspects, the determined lifespan for LPG bottling stations is set at **15 years**. This estimation aligns with industry standards and reflects the expected duration for which these facilities are anticipated to remain operational and contribute to the LPG supply chain.

3.5.4.2.4 Filling capacity

The estimation of the filling capacity for LPG bottling stations is a significant aspect of planning and optimizing the LPG supply chain in Rwanda. In order to determine the filling capacity, detailed analysis and data from Rwanda's LPG master plan (GLPGP, 2020) are utilized.

The master plan takes into account various factors, including filling plant quantities estimations and the projected yearly filling capacity per region. By considering these factors, it becomes possible to ascertain the maximum filling capacity that can be achieved by each individual bottling station.

Based on the comprehensive analysis conducted, it is determined that the approximate maximum filling capacity per plant is **35,000 ton yearly**. This estimation serves as a pivotal parameter for understanding the capabilities and potential output of LPG bottling stations within the supply chain[2].

3.5.4.2.5 Overnight costs

The estimation of overnight costs for LPG bottling stations plays a crucial role in understanding the financial implications of establishing and operating these facilities within Rwanda's LPG supply chain. To derive these estimations, the analysis heavily relies on the comprehensive data and insights provided in Rwanda's LPG master plan (GLPGP, 2020).

Within the master plan, careful consideration is given to various factors that impact the establishment of new filling plants. This includes assessing the required number of filling plants per region for their plans on an annual basis, as well as estimating the investment requirements associated with each region.

Based on the analysis conducted on said metrics, it can be inferred that the approximate overnight costs for a bottling station in Rwanda amount to **USD7,000,000**. These costs encapsulate a wide range of essential expenses involved in the establishment and operation of the facility. They encompass elements such as infrastructure development, which may include construction, electrical work, and site preparation. Additionally, the costs encompass the acquisition of specialized equipment necessary for filling, handling, and storing LPG. Compliance with regulatory requirements, including permits, licensing, and safety measures, is also considered in the estimation.

3.5.4.2.6 FOM

To derive these estimations, valuable insights are drawn from the detailed information provided in Rwanda's LPG master plan (GLPGP, 2020). Within the master plan, careful consideration is given to various cost components that contribute to the overall fixed costs

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[2] MT = 83.3 12kg-equivalent cylinders

of operating a bottling station. One significant factor is the total staff costs, which are estimated to be USD87,100 for a bottling station with an annual tonnage of approximately 35 KT. These staff costs encompass the salaries, benefits, and associated expenses related to the skilled personnel required for the efficient and effective functioning of the bottling station.

In addition to the staff costs, the master plan further specifies that other fixed costs for the bottling stations are expected to amount to three times the estimated staff costs. This broader category of fixed costs includes various non-personnel-related expenses such as facility maintenance, utilities, equipment leasing, insurance, and administrative expenses. By considering these additional fixed costs, a more comprehensive estimation of the total fixed costs for bottling stations can be derived.

Based on the determination in the master plan, the total estimated fixed costs for bottling stations amount to **USD348,400**. This figure encompasses both the staff costs and other associated fixed costs.

3.5.4.2.7 VOM

The estimation of variable costs for LPG bottling stations is a critical aspect for understanding the financial dynamics and operational expenses associated with these facilities in Rwanda's LPG supply chain. The estimation process draws valuable insights from the detailed information provided in Rwanda's LPG master plan (GLPGP, 2020).

Within the master plan, a key aspect considered is the filling cost associated with LPG bottling. It is noted that the estimated filling cost per metric ton (TON) ranges from US USD35 to USD77, depending on the volume being filled. This range takes into account the economies of scale, where larger volumes tend to result in lower filling costs. This understanding reflects the industry's dynamics and provides a valuable benchmark for estimating variable costs in bottling stations.

To determine the specific variable cost for the bottling plants analyzed in this model, the filling plant sizes outlined in the master plan are considered. The sizes presented range from approximately 7 to 35 KT per year. Based on the assumption that the filling capacity of the analyzed bottling plants aligns with the upper end of this spectrum, as stated in previous sections, an estimation of **USD35 per ton** is selected as the variable cost, a value that represents the lower end of the estimated filling cost range.

3.5.4.3 Warehouses

These facilities receive filled LPG cylinders directly from bottling stations. Once received, these cylinders are stored within warehouses, strategically positioned in proximity to demand points. This positioning optimizes the distribution process, allowing for quick and efficient access to LPG cylinders when they are required for consumer use.

3.5.4.3.1 LPG wholesale license

This license is issued by the appropriate regulatory authority and is required for businesses engaged in the wholesale distribution of LPG from warehouses. In this section, the focus will be on estimating the parameters associated with obtaining and renewing the LPG wholesale license for warehouses, taking into account the fees and validity period established by the regulatory authority (RURA, 2018).

<u>Application Fee</u>

The application fee for obtaining the LPG wholesale license for warehouses is set at **100,000 RWF**. This fee covers the administrative costs associated with processing the license application, conducting necessary evaluations, and ensuring compliance with regulations. This application fee must be paid both if it is the first time applying for the license and if the application is being for a renewal of an already approved license.

<u>License Fee</u>

Both the initial application and subsequent renewals of the LPG wholesale license for warehouses require a license fee of **1,000,000 RWF**. This fee covers the costs for obtaining and maintaining the license, which includes regulatory oversight, monitoring of wholesale operations, and ensuring compliance with safety standards and regulations.

Validity

The LPG wholesale license for warehouses is valid for a period of **5 years**. After the initial application, the license must be renewed every 5 years to continue engaging in wholesale activities. The renewal process involves submitting the required documents and paying the license fee again.

3.5.4.3.2 Lifetime

The estimation of the lifespan for warehouses is based on the assumptions outlined in Rwanda's LPG master plan (GLPGP, 2020). When considering the economic aspects of the industry, the plan takes into account several factors that affect firm and sector economics. As per industry conventions, one key assumption made is that a depreciation period of 15 years is suitable for bottling plants.

Given that the purpose of this lifespan estimation within the model primarily focuses on evaluating economic factors, it is determined that a lifespan of **15 years** is appropriate for warehouses. This assumption considers the lifespan of various components such equipment (including pallets and cages), and it is understood to be extended to warehouse operations. By setting the estimated lifespan of warehouses at 15 years, it is believed that this assumption adequately captures the typical usage and economic considerations of such facilities within the LPG supply chain.

3.5.4.3.3 Overnight costs

The estimation of overnight costs for warehouses draws insights from a report conducted by the World Bank Group (2009). The report aims to provide quantitative indicators on various aspects, including regulations related to starting a business, obtaining construction permits, securing electricity, and registering property.

Within the report, an estimated value is presented for the overnight costs associated with a warehouse spanning 1300 square meters. According to the findings, the estimated overnight costs for such a warehouse amount to RWF 32,408,957.30. Nonetheless, this initial estimation, originating from 2009, warrants adjustment to account for the subsequent inflationary trends witnessed within the country. Over the course of the ensuing 14 years, the country has experienced a nearing 120% escalation in prices (Worlddata.info, n.d.). Consequently, the revised estimate for the overnight costs of the warehouse amounts to **71,105,252.32 RWF**. This value serves as a reliable estimation for the overnight costs incurred in operating a warehouse within the context of Rwanda's business environment.

3.5.4.3.4 FOM

The estimation of fixed costs for warehouses in Rwanda's LPG supply chain is informed by the details provided in the LPG master plan (GLPGP, 2020). This comprehensive plan offers valuable insights into the staffing requirements and associated costs for warehouse operations.

According to the master plan, the staffing requirements for a warehouse can be determined based on various roles and responsibilities. For instance, assuming a scenario that requires 1 manager, 1 manager assistant, 2 accountants, 1 safety manager, 2 maintenance workers, and 4 guards, the total staff costs for this case would amount to USD38,700. These costs include salaries, benefits, and other personnel-related expenses necessary to maintain an effective and secure warehouse operation.

Additionally, drawing a parallel to the estimation approach used for bottling stations in the master plan, it can be established that other fixed costs will amount to three times the estimated staff costs. Therefore, based on this determination, the total fixed cost estimation for warehouses is **USD154,800**. This value represents the sum of various fixed expenses such as rent, utilities, insurance, maintenance, and other operational costs associated with warehouse management.

3.5.4.3.5 VOM

Estimating the variable costs for warehouses in the context of Rwanda's LPG supply chain poses certain challenges due to the lack of specific information on this aspect. However, it is reasonable to consider that variable costs for warehouses may be **negligible** compared to the significant fixed costs involved in their operation.

Given this assumption, the estimation of fixed costs for warehouses is deemed sufficient to account for the overall expenses associated with warehouse management. The reasoning behind this assumption lies in the understanding that the main warehouse expenses, such as rent, utilities, insurance, maintenance, and other operational costs, do not significantly vary based on the tonnage of LPG stored. However, it is essential to acknowledge that this estimation may not capture the full range of potential variable costs that could be relevant to specific warehouse operations.

3.6 COST MODEL

3.6.1 INTRODUCTION

This simplified model serves as a starting point to identify the primary cost drivers within the LPG supply chain. By considering a scenario where there is only one unit of each infrastructure component—namely, a single LPG depot, a single bottling station, and a single warehouse—the fundamental costs associated with each stage of the supply chain can be isolated and analysed.

The objective of this model is to gain a comprehensive understanding of the cost structure in a simplified setting, to establish a solid foundation for further analysis. By simulating a linear supply chain with one unit of each infrastructure component, the key cost factors can be identified without the complexity introduced by multiple facilities or interdependencies among them.

Throughout this thesis, the aim is to explore the various cost elements involved in the LPG supply chain, including transportation, storage, handling, and operational expenses. By focusing on a simplified scenario initially, it is possible discern the cost drivers and examine their impacts on the overall supply chain performance. This theoretical exercise will enable to develop a robust cost model, which can later be expanded to encompass more complex and realistic supply chain configurations.

In the subsequent sections, the methodology employed in this model will be presented, detailing the key cost components considered, as well as the assumptions and limitations of our analysis. The model results are the annualized costs based on the base year inputs.

3.6.2 STRUCTURE

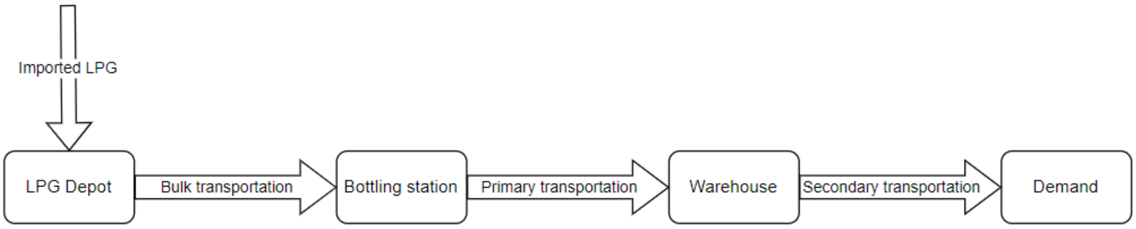


Figure 6. Simple model's structure. Source: Own elaboration.

The logical structure of the simplified LPG supply chain, as previously described, is depicted in Figure 6. This figure illustrates the sequential flow of LPG from its importation into the region to the retailer, highlighting the key infrastructure components and transportation routes involved.

At the heart of this supply chain is a single LPG depot, which serves as the primary storage facility for bulk LPG. Even though, typically the depot can receive LPG from various sources, such as refineries or import terminals, in this case, given the conditions of Rwanda, previously explained, the depot only receives LPG from importations. Said LPG is held there until further distribution is required.

The transportation between the LPG depot and the bottling station is a crucial link in the supply chain. In order to carry the bulk LPG from the depot to the bottling station, specialized transport vehicles, such as LPG tank trucks, are utilized in this process. Some elements as vehicle capacity, route planning and safety measures are needed in order to guarantee an efficient and safe transportation during this stage of the supply chain.

Once at the bottling station the bulk LPG is transferred into the containers needed for its distribution and use by the final customers. Said containers can be cylinders or smaller tanks. The late ones are used by large LPG consumers, as restaurants, hospitals, or schools.

Following the bottling process, the packaged LPG containers are transported to a central warehouse. This infrastructure acts as a temporary storage facility, enabling the efficient management of inventory and facilitating the coordination of distribution to the final retail points. This transportation leg from the bottling station to the warehouse, is called the primary transportation, it requires of good planning and great coordination to be able to ensure that it is made in a timely and cost-effective manner.

In the final stage of the LPG supply chain, the transportation of cylinders and small bulk tanks from the central warehouse to the various retail points within the covered region is accomplished through a process known as secondary transportation. Unlike the primary transportation phase that involves larger vehicles for long-distance movement, secondary transportation employs smaller vehicles specifically designated for local distribution, enabling them to navigate narrow streets and deliver LPG to retailers in densely populated areas or remote locations. One of the key objectives of secondary transportation is to maintain sufficient stock levels at each retail point to meet the ongoing demand of consumers, to avoid stockouts and ensuring customer satisfaction.

3.6.3 COST BREAKDOWN ANALYSIS

Next, the breakdown of the total annual costs in this simple scenario will be presented. The following equation, Eq. (1), presents the computation of the overall costs. As it can be observed, it comprises costs originating from cylinders, costs arising from total transportation, costs stemming from total infrastructure, and costs associated with LPG importation in the region.

$$C_{tot} = C_{cyl} + C_{trans_{tot}} + C_{infra_{tot}} + C_{LPG_{imp}}$$

Eq. (1)

$C_{tot}: Total\ cost\ [\frac{USD}{year}]$

$C_{cyl}: Total\ cost\ of\ cylinders\ [USD/year]$

$C_{trans_{tot}}: Total\ cost\ of\ transportation\ [\frac{USD}{year}]$

$C_{infra_{tot}}: Total\ cost\ of\ infraestructure\ [\frac{USD}{year}]$

$C_{LPG_{imp}}: Cost\ of\ LPG\ imported\ \left[\frac{USD}{year}\right]$

It is relevant to highlight that a bottom-up approach will be used to calculate all the costs within the supply chain. This approach is adopted primarily due to the presence of losses that occur during the various stages of the process. By adopting a bottom-up approach, the model takes into consideration the losses that occur during storage, transportation, and distribution. These losses can arise from factors such as evaporation, leakage, or incomplete transfer during loading and unloading operations. As a result, the initial quantity of LPG required at the top of the supply chain must be adjusted to compensate for these losses, ensuring that the final given demand is adequately met. Therefore, the bottom-up approach provides a systematic and detailed framework to compute all the costs within the LPG supply chain, taking into account the losses incurred at each relevant stage. This approach ensures that the model accurately reflects the actual quantity of LPG required at the top of the supply chain, enabling effective decision-making and resource allocation to meet the final demand.

3.6.3.1.1 Cylinders

In order to accurately assess the costs of cylinders, this section will consider the initial investment costs, which includes the procurement cost of the cylinders, shown in Eq. (2). However, it is relevant to note that there is another cost associated to the cylinders, recurring expenses related with their maintenance and handling which encompass refurbishment, periodic testing, and safety measures required to ensure their continued use, known as the requalification process. Nevertheless, said requalification costs will be considered in a latter section, to combine it with the bottling station costs.

$$C_{cyl} = \sum_{i=1}^{n_{size\ cyl}} C_{cyl_{acq_i}} = \sum_{i=1}^{n_{size\ cyl}} \frac{(Q_{cyl_i} * P_{cyl_{emp_i}}) * r}{[1-(1+r)^{-LT_{cyl_i}}]}$$

Eq. (2)

$C_{cyl}: Total\ cost\ of\ cylinders\ [USD/year]$

$C_{cyl_{acq_i}}: Cost\ of\ acquiring\ all\ cylinders\ size\ i\ \left[\frac{USD}{year}\right]$

$Q_{cyl_i}: Quantity\ of\ cylinders\ size\ i\ [cylinders]$

$P_{cyl_{emp_i}}: Price\ of\ empty\ cylinders\ size\ i\ [\frac{USD}{cylinder}]$

$r: discount\ rate\ [\%]$

$LT_{cyl_i}: Lifetime\ of\ cylinder\ size\ i\ [years]$

$n_{size\ cyl}: number\ of\ cylinder's\ sizes\ considered$

To calculate the annual cost, the fixed annual discount or interest rate is applied to the initial investment, taking into account the time value of money. This discount rate represents the opportunity cost of utilizing capital in this particular investment rather than in alternative ventures. By discounting the initial investment, the annual cost reflects the equivalent value of that money over the years. Moreover, the expected lifetime of the acquired cylinders is a crucial factor in the cost computation. It represents the anticipated duration for which the cylinders are expected to remain in service before they need to be replaced. This estimation takes into account factors such as wear and tear, maintenance requirements, and technological advancements that may render the existing cylinders obsolete. By incorporating the fixed annual discount or interest rate and the expected lifetime of the cylinders, the first component of the equation provides a comprehensive evaluation of the annual costs associated with cylinder acquisition and maintenance. This information enables decision-makers to assess the financial implications and make informed choices regarding cylinder management strategies within the LPG supply chain.

The computation to obtain the number of cylinders of each size is shown in Eq. (3). It is obtained based on the given data of the total LPG demand and taking into account the size of each type of container and the percentage of the total demand represented by each type of container. It is also important to note that the equation is multiplied by 1000 in order to convert the LPG final demand, expressed in TON, to kg, since those are the units in which the size of a cylinder is given.

$$Q_{cyl} = \sum_{i=1}^{n_{size\ cyl}} \frac{Q_{LPG_{dem}} * 1000 * Mix_{size_i}}{Size_{cyl_i} * TO_i}$$

Eq. (3)

$Q_{cyl}: Quantity\ of\ cylinders\ \ [cylinders]$

$Q_{LPG_{dem}}: LPG\ final\ demand\ [MT]$

$Mix_{size}: Percentage\ of\ the\ total\ mix\ of\ cylinders\ of\ a\ determined\ size\ [\%]$

$Size_{cyl}: Size\ of\ a\ cylinder\ [kg/cyl]$

$TO_i: Turnover\ rate\ for\ cylinders\ size\ i$

$n_{size\ cyl}: number\ of\ cylinder's\ sizes\ considered$

3.6.3.1.2 Transportation

The second component of the annual total cost equation pertains to the expenses linked to the transportation aspect of the supply chain. As shown in the Eq. (4), it encompasses the comprehensive costs of three distinct transportation stages: secondary transportation, and primary transportation, and bulk transportation, which were previously elucidated.

$$C_{trans_{tot}} = C_{sectrans} + C_{primtrans} + C_{bulktrans}$$

Eq. (4)

$C_{trans_{tot}}: Total\ cost\ of\ transportation\ [\frac{USD}{year}]$

$C_{sectrans}: Cost\ of\ secondary\ transportation\ [\frac{USD}{year}]$

$C_{primtrans}: Cost\ of\ primary\ transportation\ [\frac{USD}{year}]$

$C_{bulktrans}: Cost\ of\ bulk\ transportation\ [\frac{USD}{year}]$

<u>Secondary transportation</u>

Adopting a bottom-up approach, the first transportation stage to be considered in the analysis is the secondary transportation, which involves the distribution of LPG from the warehouses to the retailers, shown in Eq. (5). As depicted in the equation, the total cost of secondary transportation encompasses several key factors. These factors include the cost of acquiring the vehicles, the fuel expenditure incurred during the transportation routes, as well as the fixed operating cost (FOM), variable operating cost (VOM) and licence fees.

$$C_{sectrans} = C_{sectrans_{inv}} + C_{fuel_{sectrans}} + C_{sectrans_{FOM_{tot}}} + C_{sectrans_{VOM_{tot}}} + C_{sectrans_{lic}}$$

Eq. (5)

$C_{sectrans}: Cost\ of\ secondary\ transportation\ [\frac{USD}{year}]$

$C_{sectrans_{inv}}: Cost\ of\ acquiring\ all\ secondary\ vehicles\ \left[\frac{USD}{year}\right]$

$C_{fuel_{sectrans}}: Cost\ of\ all\ the\ fuel\ used\ by\ secondary\ vehicles\ \left[\frac{USD}{year}\right]$

$C_{sectrans_{FOM_{tot}}}: FOM\ of\ all\ secondary\ vehicle\ [\frac{USD}{year}]$

$C_{sectrans_{VOM_{tot}}}: VOM\ of\ all\ secondary\ vehicles\ [\frac{USD}{year}]$

$C_{sectrans_{lic}}: Cost\ of\ seconday\ transportation\ licenses\ [\frac{USD}{year}]$

This initial focus allows for a detailed examination of this particular step within the supply chain. By first examining the secondary transportation, valuable insights can be gained regarding the specific challenges, costs, and dynamics involved in delivering LPG from the warehouses to the retailers. This detailed understanding serves as a foundation for further analysis and enables the identification of potential patterns or commonalities with the primary and bulk transportation stages. Subsequently, an exploration will be conducted to determine if any analogous characteristics or similarities exist between this stage and the primary and bulk transportation stages. Analysing potential analogies between the secondary transportation and the primary and bulk transportation stages offers the opportunity to leverage existing knowledge, best practices, and cost-saving strategies. It allows for the transfer of successful approaches and lessons learned from one stage to another, potentially optimizing the overall transportation efficiency within the supply chain.

The cost of acquiring vehicles accounts for the initial investment required to procure the necessary fleet for secondary transportation, shown in Eq. (6). This might include the purchase or lease costs of the vehicles, along with any associated expenses such as registration, insurance, or customization to meet specific transportation requirements. To calculate the annual cost, the fixed annual discount or interest rate is applied to the initial investment, taking into account the time value of money. This discount rate represents the opportunity cost of utilizing capital in this particular investment rather than in alternative ventures. By discounting the initial investment, the annual cost reflects the equivalent value of that money over the years. Moreover, the expected lifetime of the acquired secondary vehicles is an important factor in the cost computation. It represents the anticipated duration for which said vehicles are expected to remain in service before they are no longer fit to be used. Investment costs will be distributed across each case, contingent on the variable "attributable fixed costs for secondary transportation". This variable considers the percentage of the analysed resource utilized to fulfil the specific case's demand, guiding the allocation process and its calculation is shown in Eq. (7).

$$C_{sectrans_{inv}} = \frac{(P_{sectrans} * Q_{sectrans}) * r}{[1-(1+r)^{-LT_{sectrans}}]} * At_{sectrans}$$

Eq. (6)

$C_{sectrans_{inv}}: Cost\ of\ acquiring\ all\ secondary\ vehicles\ \left[\frac{USD}{year}\right]$

$Q_{sectrans}: Quantity\ of\ secondary\ vehicles\ needed\ in\ the\ whole\ region\ [vehicles]$

$P_{sectrans}: Price\ of\ acquiring\ secondary\ vehicles\ [USD/vehicles]$

$r: discount\ rate\ [\%]$

$LT_{sectrans}: Lifetime\ of\ secondary\ vehicles\ [year]$

$At_{sectrans}: Atributable\ fixed\ cost\ for\ secondary\ transportation\ [\%]$

$$At_{sectrans} = \frac{trips_{sectrans}}{workdays}$$

Eq. (7)

$trips_{sectrans}: Secondary\ transportation\ trips\ [\frac{trips}{year * vehicle}]$

$workdays: Working\ days\ in\ a\ year\ [\frac{days}{year * vehicle}]$

In Eq. (7) it shown that the attributable fixed costs for secondary transportation are computed based on the working days and the amount of trips made yearly by each vehicle, shown in Eq. (8), this is under the assumption that distribution routes are being optimized in a way that each trips has a duration equivalent to one work shift. The purpose of using Eq. (8) is to determine the optimal allocation and utilization of secondary vehicles in order to fulfil the cylinder transportation requirements efficiently. By taking into account the capacity of each vehicle, which refers to the maximum number of cylinders that can be accommodated in a single trip, the equation assists in determining the appropriate number of trips needed. The result obtained aids in optimizing the allocation of cylinders across the available secondary vehicles, ensuring that the demand is met while maximizing the efficiency of transportation operations.

$$trips_{sectrans} = \frac{Q_{LPG_{Sectrans}}}{Q_{sectrans} * Cap_{sectrans}}$$

Eq. (8)

$trips_{sectrans}: Secondary\ transportation\ trips\ [\frac{trips}{year*vehicle}]$

$Q_{LPG_{Sectrans}}: LPG\ needed\ for\ secondary\ transportation\ [12\ kg - eq\ cyl]$

$Q_{sectrans}: Quantity\ of\ secondary\ vehicles\ needed\ in\ the\ whole\ region\ [vehicles]$

$Cap_{sectrans}: Capacity\ of\ secondary\ vehicle\ [\frac{12\ kg-eq\ cylinders}{vehicle*trip}]$

As previously stated, the study takes a bottom to top approach and considered the potential losses of each stage analysed in the supply chain. In Eq. (9) it is shown how the losses impact the amount of LPG considered for each stage.

$$Q_{LPG_{Sectrans}} = \frac{Q_{LPG_{Dem}}}{(1 - L_{sectrans})}$$

Eq. (9)

$Q_{LPG_{Sectrans}}: LPG\ needed\ for\ secondary\ transportation\ [12\ kg - eq\ cyl]$

$Q_{LPG_{dem}}: LPG\ final\ demand\ [12\ kg - eq\ cyl]$

$L_{sectrans}: Secondary\ transportation'\ losses\ [\%]$

Fuel expenditure plays a substantial role in the overall cost of secondary transportation, as it encompasses the ongoing fuel consumption during secondary transportation routes. As shown in Eq. (10), this cost factor is influenced by both the prevailing market prices of fuel and the fuel efficiency of the vehicles employed for secondary transportation. The cost of purchasing fuel directly impacts the financial outlay, as it is subject to market fluctuations and variations in global energy prices. Changes in fuel prices can have a significant impact on the overall cost of secondary transportation, especially considering the extensive distances covered and the volume of fuel consumed by the vehicles. Moreover, the fuel consumption rate of the transportation vehicles is a crucial aspect to consider. The efficiency of the vehicles in terms of fuel consumption determines the amount of fuel required to cover a given distance. Vehicles with higher fuel efficiency will consume less fuel per unit of distance travelled, thus reducing the overall fuel expenditure.

$$C_{fuel_{sectrans}} = \frac{Q_{secroad_{tot}} * Q_{trip_{sectrans}} * Q_{sectrans} * F_{sectrans} * P_{fuel_{sectrans}}}{100}$$

Eq. (10)

$C_{fuel_{sectrans}}: Cost\ of\ all\ the\ fuel\ used\ by\ seocndary\ vehicles\ \left[\frac{USD}{year}\right]$

$Q_{secroad_{tot}}: Total\ amount\ of\ roads'distance\ related\ to\ secundary\ transportation\ [\frac{km}{trip}]$

$Q_{trip_{sectrans}}: Trips\ per\ year\ made\ by\ each\ secondary\ vehicle\ [\frac{trips}{year*vehicle}]$

$Q_{sectrans}: Quantity\ of\ secondary\ vehicles\ needed\ in\ the\ whole\ region\ [vehicles]$

$F_{sectrans}: Fuel\ consumption\ of\ secondary\ vehicles\ [\frac{L}{100km}]$

$P_{fuel_{sectrans}}: Price\ of\ fuel\ used\ by\ secondary\ vehicles\ [\frac{USD}{L}]$

Is should be highlighted that the distance considered for each trip has the underlaying assumption that trips for secondary transportation are designed in a way that creates a round trip. This is due to the high expected number of retailers in each region, therefore when route-planning the routes are not going to be radial. Another detail in Eq. (10) is that it is divided by 100 since it considers that the units of fuel consumption are typically given in litres per 100 kilometres.

The fixed operating and maintenance cost (FOM), presented in Eq. (11), comprises expenses that remain relatively consistent irrespective of the distance travelled or the load carried during secondary transportation. These costs encompass various aspects necessary for operating the secondary transportation fleet effectively. Included in the FOM cost might be expenses related to vehicle maintenance and repairs, which are essential to ensure the fleet's optimal functioning and longevity. Regular servicing, inspections, and necessary repairs contribute to maintaining the vehicles in good working condition, minimizing the risk of breakdowns or operational disruptions. Insurance premiums can be another component of the FOM cost. It is crucial to protect the secondary transportation fleet against potential risks, such as accidents, theft, or damage, by obtaining comprehensive insurance coverage. The insurance premiums contribute to mitigating financial liabilities in the event of unforeseen circumstances. Taken into account the information found in the parameters estimation section previously stated, the fixed operation and maintenance costs will be computed based on the variable costs, as shown in Eq. (11), since the data known is the relationship between those two. It is also relevant to highlight that for this calculation the attributable fixed cost percentage will also be taken into account.

$$C_{sectrans_{FOM_{tot}}} = C_{sectrans_{FOM}} * C_{sectrans_{VOM_{tot}}} * At_{sectrans}$$

Eq. (11)

$C_{sectrans_{FOM_{tot}}}: FOM\ of\ all\ secondary\ vehicle\ [\frac{USD}{year}]$

$C_{sectrans_{FOM}}: FOM\ of\ secondary\ vehicles\ expressed\ as\ a\ percentage\ of\ VOM\ [\%]$

$At_{sectrans}: Atributable\ fixed\ cost\ for\ secondary\ transportation\ [\%]$

Conversely, the variable operating cost (VOM), presented in Eq. (12), comprises expenses that vary based on the distance travelled. These costs are directly associated with the day-to-day transportation operations and fluctuate accordingly. Driver salaries form a significant component of the variable operating cost. The cost of employing drivers to operate the secondary transportation vehicles varies depending on factors such as working hours, overtime, and any additional allowances or benefits provided to the drivers. These costs are directly related to the distance covered and the number of trips made by the drivers. Toll fees could also contribute to the variable operating cost. Depending on the routes taken, toll charges are incurred to access certain roads or bridges, which can vary based on the distance travelled and the specific toll rates applicable to the transportation route.

$$C_{sectrans_{VOM_{tot}}} = C_{sectrans_{VOM_{ind}}} * Q_{secroad_{tot}} * Q_{trip_{sectrans}} * Q_{sectrans}$$

Eq. (12)

$C_{sectrans_{VOM_{tot}}}: VOM\ of\ all\ secondary\ vehicles\ [\frac{USD}{year}]$

$C_{sectrans_{VOM_{ind}}}: VOM\ of\ a\ secondary\ vehicle\ [\frac{USD}{km}]$

$Q_{secroad_{tot}}: Total\ amount\ of\ distance\ of\ the\ roads\ related\ to\ secundary\ trans.\ [\frac{km}{trip}]$

$Q_{trip_{sectrans}}: Trips\ per\ year\ made\ by\ each\ secondary\ vehicle\ [\frac{trips}{year*vehicle}]$

$Q_{sectrans}: Quantity\ of\ secondary\ vehicles\ needed\ in\ the\ whole\ region\ [vehicles]$

Lastly, the transportation license fee costs, as defined in Eq. (13), encapsulates expenses incurred as a result of regulatory obligations imposed on secondary transportation operations. These costs are not contingent on the distance travelled but rather stem from adherence to legal and administrative requirements. The transportation license fee represents a fixed financial commitment that must be fulfilled to enable lawful secondary transportation activities, since it is a fixed cost, it is also subjected to the attributable fixed cost percentage.

$$C_{sectrans_{lic}} = \frac{License_{fee_{sectrans}} * r}{[1 - (1 + r)^{-license_{sectrans_{val}}}]} * At_{sectrans}$$

Eq. (13)

$C_{sectrans_{lic}}: Cost\ of\ seconday\ transportation\ licenses\ [\frac{USD}{year}]$

$License_{fee_{sectrans}}: License\ fee\ for\ secondary\ transportation\ [USD]$

$r: discount\ rate\ [\%]$

$license_{sectrans_{val}}: validity\ of\ license\ for\ secondary\ transportation\ [USD]$

$At_{sectrans}: Atributable\ fixed\ cost\ for\ secondary\ transportation\ [\%]$

Primary transportation

The calculations for primary transportation are analogous to those for secondary transportation. However, there is one notable difference worth highlighting: instead of using the variable $Q_{sectran}$, the variable $Q_{primtran}$ will be employed to account for potential losses that may occur within the warehouses and primary transportation process. By incorporating $Q_{primtran}$ into the equations, the model considers the possibility of losses during storage and handling within the warehouses and cylinder transportation, as presented in Eq. (14). These losses could result from factors such as leakage, evaporation, or other operational inefficiencies that can impact the overall quantity of cylinders available for transportation. Additionally, Eq. (15) shows how the number of cylinders required in warehouse considering the losses in it are calculated.

$$Q_{LPG_{primtrans}} = \frac{Q_{LPG_{WH}}}{(1 - L_{primtrans})}$$

Eq. (14)

$Q_{LPG_{primtrans}}: LPG\ needed\ for\ primary\ transportation\ [12\ kg - eq\ cyl]$

$Q_{LPG_{WH}}: LPG\ needed\ for\ warehouse\ [12\ kg - eq\ cyl]$

$L_{primtrans}: Primary\ transportation'\ losses\ [\%]$

$$Q_{LPG_{WH}} = \frac{Q_{LPG_{sectrans}}}{(1 - L_{WH})}$$

Eq. (15)

$Q_{LPG_{WH}}: LPG\ needed\ for\ warehouse\ [12\ kg - eq\ cyl]$

$Q_{LPG_{sectrans}}: LPG\ needed\ for\ secondary\ transportation\ [12\ kg - eq\ cyl]$

$L_{WH}: Warehouse'\ losses\ [\%]$

Furthermore, unlike secondary transportation, primary vehicles typically do not engage in round-trip deliveries. When estimating the cost of fuel for primary transportation, similarly as within secondary transportation, the calculations take into account the distance travelled by each vehicle. However, the calculations are adjusted to reflect the fact that primary vehicles generally make one-way trips without delivering goods on their return journey, this is represented in Eq. (16) by multiplying $Q_{trip_{primtrans}}$ by two. This distinction ensures that the fuel costs are accurately represented in the model. By accounting for the one-way trips made by primary vehicles, the model effectively captures the actual fuel consumption required for their specific transportation operations. This ensures a more accurate estimation of the fuel costs associated with primary transportation, considering the unique characteristics of their delivery routes.

$$C_{fuel_{primtrans}} = \frac{Q_{primroad_{tot}} * Q_{trip_{primtrans}} * 2 * Q_{ptimtrans} * F_{primtrans} * P_{fuel_{primtrans}}}{100}$$

Eq. (16)

Bulk transportation

The calculations for bulk transportation are analogous to those for primary and secondary transportation. However, as it happened in the primary transportation case, there is one notable difference worth highlighting: when calculating $Q_{trip_{bulktrans}}$, needed to obtain other variables, such as $C_{fuel_{sectrans}}$, instead of using the variable $Q_{LPG_{sectrans}}$ as made in Eq. (9), the calculation then used is shown in Eq. (17)

$$trips_{bulktrans} = \frac{Q_{LPG_{bulktrans}}}{Q_{bulktrans} * Cap_{bulktrans}}$$

Eq. (17)

$trips_{bulktrans}: Bulk\ transportation\ trips\ [\frac{trips}{year*vehicle}]$

$Q_{LPG_{bulktrans}}: LPG\ needed\ for\ bulk\ transportation\ [MT]$

$Q_{bulktrans}: Quantity\ of\ bulk\ vehicles\ needed\ in\ the\ whole\ region\ [vehicles]$

$Cap_{bulktrans}: Capacity\ of\ bulk\ vehicle\ [\frac{MT}{vehicle*trip}]$

As it has happened before, variable $Q_{LPG_{Dep}}$will be employed to account for potential losses that may occur within the bottling stations, as shown in Eq. (18). By incorporating $Q_{LPG_{Dep}}$ into the equations, the model considers the possibility of losses during the bottling station operations. Within the bottling stations, there might be some losses that cannot be avoided during the process. For example, small amounts of LPG might be lost when transferring it from to the smaller containers, either due to evaporation leakage, due to human error, or measurements errors.

$$Q_{LPG_{bulk}} = \frac{Q_{LPG_{BS}}}{(1 - L_{bulktrans})}$$

Eq. (18)

$Q_{LPG_{bulk}}: LPG\ needed\ for\ bulk\ transportation\ [MT]$

$Q_{LPG_{BS}}: LPG\ needed\ for\ bottling\ station\ [MT]$

$L_{bulktrans}: Bulk\ transportation'\ losses\ [\%]$

It is shown in Eq. (19) how to obtain the LPG needed in the bottling station taking into account the losses in the plant, derived from the LPG in primary transportation since the approach taken is bottom to top. However, it is important to highlight that since the LPG in primary transportation is measured in cylinders (12 kg-equivalent), a conversion factor is included in the equation to obtain the LPG needed in the bottling station in bulk units (MT).

$$Q_{LPG_{BS}} = \frac{Q_{LPG_{primtrans}} * \frac{12}{1000}}{(1 - L_{BS})}$$

Eq. (19)

$Q_{LPG_{BS}}: LPG\ needed\ for\ bottling\ station\ [MT]$

$Q_{LPG_{primtrans}}: LPG\ needed\ for\ primary\ transportation\ [12\ kg - eq\ cyl]$

$L_{BS}: Bottling\ station'\ losses\ [\%]$

3.6.3.1.3 Infrastructure

The third component of the annual total cost equation accounts for the costs related to infrastructure within the LPG supply chain. As shown in Eq. (20), this component encompasses the total costs associated with warehouses, bottling stations, and LPG depots, as previously discussed.

$$C_{infra_{tot}} = C_{WH} + C_{BS} + C_{Dep}$$

Eq. (20)

$C_{infra_{tot}}: Total\ cost\ of\ infraestructure\ [\frac{USD}{year}]$

$C_{WH}: Total\ cost\ of\ warehouses\ [\frac{USD}{year}]$

$C_{BS}: Total\ cost\ of\ bottling\ stations\ [\frac{USD}{year}]$

$C_{Dep}: Total\ cost\ of\ LPG\ Depots\ [\frac{USD}{year}]$

Adopting a bottom-up approach, the first infrastructure step to be analyse in the study are the warehouses, which receive LPG cylinders via primary transportation and distribute them to the final demand considered via secondary transportation, presented in Eq. (21). As indicated in the equation, the total cost of warehouses encompasses several components, including the overnight cost of opening, building, or establishing a new warehouse, as well as the fixed operating cost (FOM), variable operating cost (VOM) and license fees.

$$C_{WH} = C_{WH_{ON}} + C_{WH_{FOM_{tot}}} + C_{WH_{VOM_{tot}}} + C_{WH_{lic}}$$

Eq. (21)

$C_{WH_{ON}}: Cost\ of\ opening\ a\ new\ warehouse\ [\frac{USD}{year}]$

$C_{WH_{FOM_{tot}}}: FOM\ of\ all\ warehouses\ [\frac{USD}{year}]$

$C_{WH_{VOM_{tot}}}: VOM\ of\ all\ warehouses\ [\frac{USD}{year}]$

$C_{WH_{lic}}: Cost\ of\ warehouse's\ licenses\ [\frac{USD}{year}]$

The initial expenses needed in establishing a new facility are included in the overnight cost of opening or constructing a new warehouse, detailed in Eq. (22). This cost includes land acquisition, building or lease charges, permissions and licenses, initial infrastructure setup, and any other upfront investments required to bring the warehouse online. Significant financial resources are required while creating a new warehouse to obtain sufficient land or premises for the operation. Land acquisition costs include purchasing or leasing the property, executing essential surveys, and obtaining any applicable permissions or zoning approvals. Costs associated with developing a warehouse or signing a lease for an existing structure fall under the construction or leasing category. In order to ensure that regulatory standards are being followed, permits and licenses are essential. These expenses cover acquiring the building permits, fire safety licenses, environmental licenses, and other licenses required to lawfully and safely run the warehouse. The first infrastructure setup is putting in place the required equipment and systems to efficiently support warehouse operations. Installing shelving, material handling equipment, lighting, security systems, and other critical infrastructure elements falls under this category. The expenses related to this phase include buying and installing the necessary infrastructural components. Investment costs will be distributed across each case, contingent on the variable "attributable fixed costs for warehouse". This variable considers the percentage of the analysed resource utilized to fulfil the specific case's demand, guiding the allocation process and its calculation is shown in Eq. (22).

$$C_{WH_{ON}} = \frac{(P_{WH_{ON}}) * r}{[1-(1+r)^{-LT_{WH}}]} * At_{WH}$$

Eq. (22)

$C_{WH_{ON}}: Cost\ of\ opening\ a\ new\ warehouse\ [\frac{USD}{year}]$

$P_{WH_{ON}}: Overnight\ cost\ of\ opening\ a\ warehouse\ [USD]$

$r: discount\ rate\ [\%]$

$LT_{WH}: Lifetime\ of\ a\ warehouse\ [years]$

$At_{WH}: Atributable\ fixed\ cost\ for\ warehouse\ [\%]$

In addition, the fixed operating cost (FOM) component of warehouse costs encompasses the consistent expenses associated with operating and maintaining the warehouses, shown in Eq. (23). These expenses remain relatively constant regardless of the volume of goods stored or the level of activity within the facility. The FOM includes various expenditures necessary for the day-to-day operations and upkeep of the warehouses. One significant aspect of the FOM is warehouse maintenance and repairs. This includes routine maintenance tasks, equipment servicing, and repairs to ensure the smooth functioning of the warehouse infrastructure. Regular maintenance helps prevent operational disruptions, extends the lifespan of warehouse assets, and ensures a safe working environment. Property taxes are another essential component of the FOM. Warehouses are subject to property taxes based on the value of the land and the facility itself. These taxes contribute to the overall fixed expenses incurred in operating the warehouses. Insurance premiums are an essential consideration for warehouse operations. Warehouse owners and operators need to protect their assets, inventory, and personnel from potential risks such as theft, fire, or natural disasters. The cost of insurance premiums is included in the FOM as a fixed operational expense. It is also relevant to highlight that for this calculation the attributable fixed cost percentage will also be taken into account.

$$C_{WH_{FOM_{tot}}} = \frac{(C_{WH_{FOM_{ind}}}) * r}{[1-(1+r)^{-LT_{WH}}]} * At_{WH}$$

Eq. (23)

$C_{WH_{FOM_{tot}}}: FOM\ of\ all\ warehouses\ [\frac{USD}{year}]$

$C_{WH_{FOM_{ind}}}: FOM\ of\ a\ Warehouse\ [\frac{USD}{year*WH}]$

$r: discount\ rate\ [\%]$

$LT_{WH}: Lifetime\ of\ a\ warehouse\ [years]$

$Q_{WH} = Total\ amount\ of\ warehouses\ in\ the\ region\ [WH]$

On the other hand, the variable operating cost (VOM) component of the warehouses' total cost is determined by the amount of LPG stored annually, shown in Eq. (24). Within the VOM, labour wages for warehouse staff remain a significant aspect. These costs encompass the compensation of employees involved in handling, monitoring, and managing the stored LPG. The number of personnel required may vary based on the volume of LPG stored and the tasks involved in maintaining proper inventory management. Additionally, the VOM includes expenses related to utilities necessary for preserving the quality and safety of the stored LPG. This comprises costs associated with electricity for climate control systems, lighting, and other essential services directly involved in LPG storage operations.

$$C_{WH_{VOM_{tot}}} = C_{WH_{VOM_{ind}}} * Q_{LPG_{WH}}$$

Eq. (24)

$C_{WH_{VOM_{tot}}}: VOM\ of\ all\ warehouses\ [\frac{USD}{year}]$

$C_{WH_{VOM_{ind}}}: VOM\ of\ a\ warehouse\ per\ a\ MT\ of\ LPG [\frac{USD}{year*MT}]$

$Q_{LPG_{WH}}: Total\ amount\ of\ LPG\ needed\ in\ warehouses\ to\ cover\ the\ final\ demand\ [MT]$

Lastly, the transportation license fee costs, as defined in Eq. (25), encapsulates expenses incurred as a result of regulatory obligations imposed on warehouse operations. These costs are not contingent on the amount of LPG stored but rather stem from adherence to legal and administrative requirements. The license fee represents a fixed financial commitment that must be fulfilled to enable lawful operation activities, since it is a fixed cost, it is also subjected to the attributable fixed cost percentage.

$$C_{WH_{lic}} = \frac{License_{fee_{WH}} * r}{[1-(1+r)^{-license_{WH_{val}}}]} * At_{WH}$$

Eq. (25)

$C_{sectrans_{lic}}: Cost\ of\ warehouse's\ licenses\ [\frac{USD}{year}]$

$License_{fee_{WH}}: License\ fee\ for\ warehouses\ [USD]$

$r: discount\ rate\ [\%]$

$license_{WH_{val}}: validity\ of\ license\ for\ secondary\ transportation\ [USD]$

$At_{WH}: Atributable\ fixed\ cost\ for\ warehouse\ [\%]$

Bottling station and LPG Depot

Bottling station and LPG Depot costs are calculated in an analogue process to the warehouse costs. However, for the LPG Depot only the license fee costs will be taken into account.

3.6.3.1.4 Import

Lastly, Eq. (26) reveals how import costs are calculated, tied to the actual amount of LPG brought in. Eq. (27) then outlines how the imported LPG volume is obtained, using a similar approach to what has been presented in previous sections.

$$C_{LPG_{imp}} = Q_{LPG_{imp}} * P_{LPG}$$

Eq. (26)

$C_{LPG_{imp}}: Cost\ of\ LPG\ imported\ \left[\frac{USD}{year}\right]$

$Q_{LPG_{imp}}: Total\ amount\ of\ LPG\ imported\ needed\ \left[\frac{MT}{year}\right]$

$P_{LPG}: Price\ of\ imported\ LPG\ [\frac{USD}{MT}]$

$$Q_{LPG_{imp}} = \frac{Q_{LPG_{Dep}}}{(1 - L_{imp})}$$

Eq. (27)

$Q_{LPG_{imp}}: Total\ amount\ of\ LPG\ imported\ needed\ \left[\frac{MT}{year}\right]$

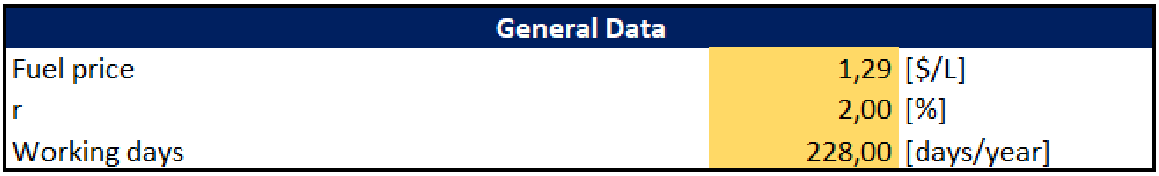
$Q_{LPG_{Dep}}: LPG\ needed\ for\ Depot\ [MT]$

$L_{imp}: Importation'\ losses\ [\%]$

Capítulo 4. CASE ANALYSIS

4.1 GENERAL INPUTS

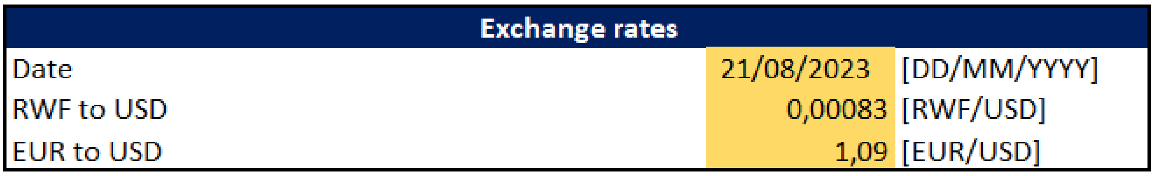
In this section the data used for the model's general inputs are presented. It is important to highlight that the model also considers inputs particular to each scenario, however, those will be shown in each case. All inputs are referred to the base year, 2023. The working days have been obtained Rwanda's holiday calendar (Timesles, 2023) and the allowed paid days off in the country (Globalexpansion, n.d)



General Data		
Fuel price	1,29	[$/L]
r	2,00	[%]
Working days	228,00	[days/year]

Table 2. Model inputs: General Data. Source: Own elaboration.

Table 2 shows the more general data, while Table 3 focuses on the exchange rates needed since some of the inputs might be in different currencies and the model aims to unify all the costs to USD.

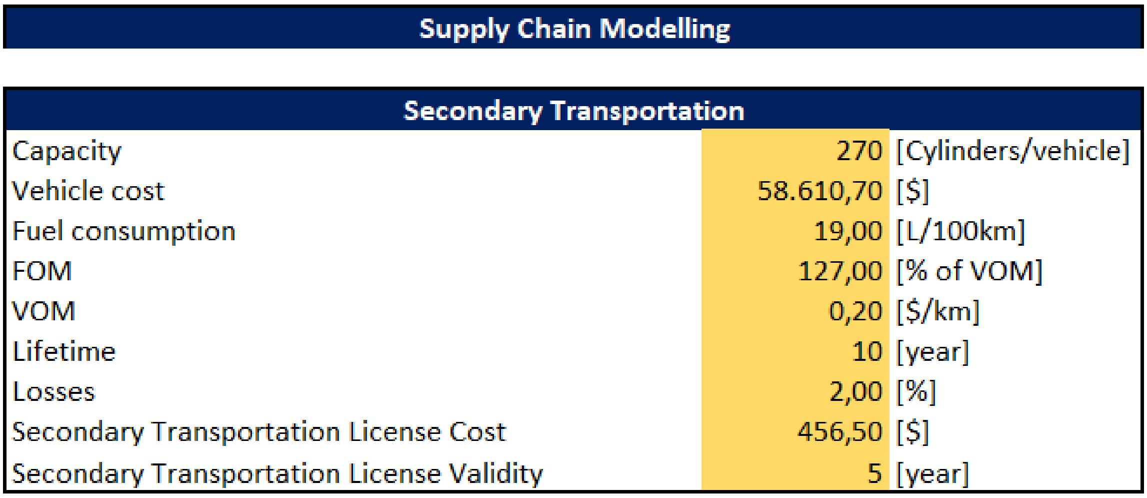


Exchange rates		
Date	21/08/2023	[DD/MM/YYYY]
RWF to USD	0,00083	[RWF/USD]
EUR to USD	1,09	[EUR/USD]

Table 3. Model inputs: Exchange rates. Source: Own elaboration.

Moreover, Table 4, Table 6 and Table 8 present the data relevant to the different transportation methods. These tables are a reflection of the parameters estimation process that has taken place in a previous section.

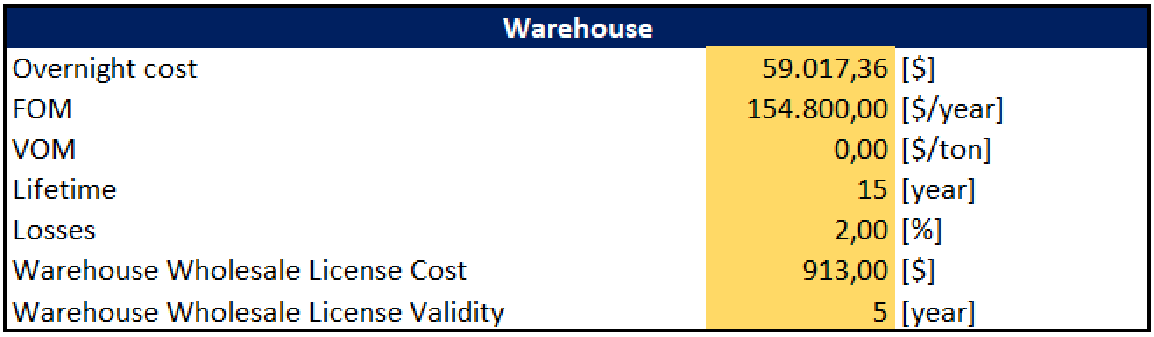
Furthermore, Table 5, Table 7 and Table 9 present the data relevant to the different infrastructures. These tables reflect the parameters estimation process that has taken place in a former section.



Supply Chain Modelling

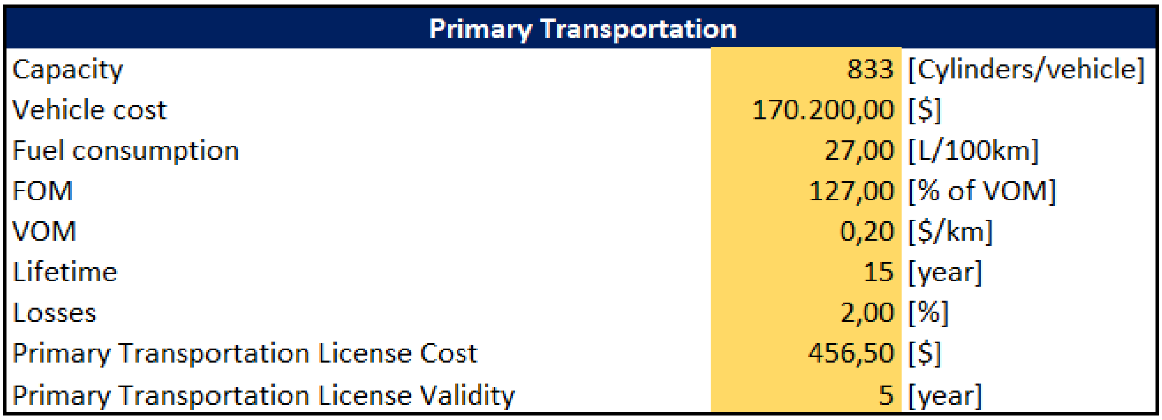
Secondary Transportation		
Capacity	270	[Cylinders/vehicle]
Vehicle cost	58.610,70	[$]
Fuel consumption	19,00	[L/100km]
FOM	127,00	[% of VOM]
VOM	0,20	[$/km]
Lifetime	10	[year]
Losses	2,00	[%]
Secondary Transportation License Cost	456,50	[$]
Secondary Transportation License Validity	5	[year]

Table 4. Model inputs: Secondary Transportation. Source: Own elaboration.



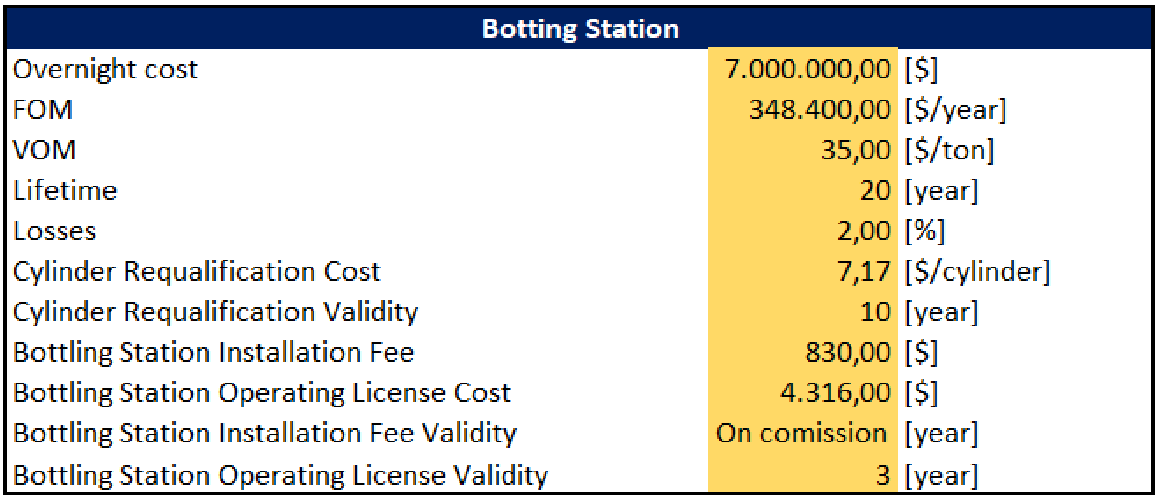
Warehouse		
Overnight cost	59.017,36	[$]
FOM	154.800,00	[$/year]
VOM	0,00	[$/ton]
Lifetime	15	[year]
Losses	2,00	[%]
Warehouse Wholesale License Cost	913,00	[$]
Warehouse Wholesale License Validity	5	[year]

Table 5. Model inputs: Warehouse. Source: Own elaboration.



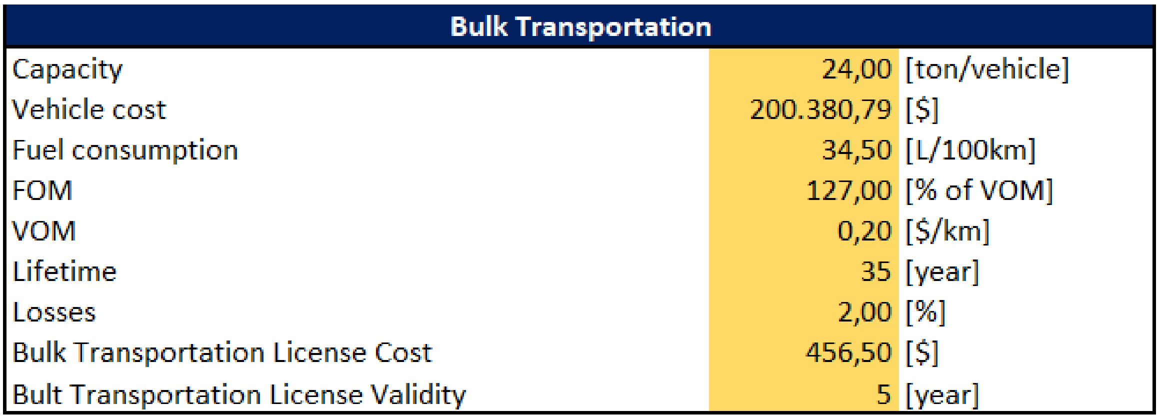
Primary Transportation		
Capacity	833	[Cylinders/vehicle]
Vehicle cost	170.200,00	[$]
Fuel consumption	27,00	[L/100km]
FOM	127,00	[% of VOM]
VOM	0,20	[$/km]
Lifetime	15	[year]
Losses	2,00	[%]
Primary Transportation License Cost	456,50	[$]
Primary Transportation License Validity	5	[year]

Table 6. Model inputs: Primary Transportation. Source: Own elaboration.



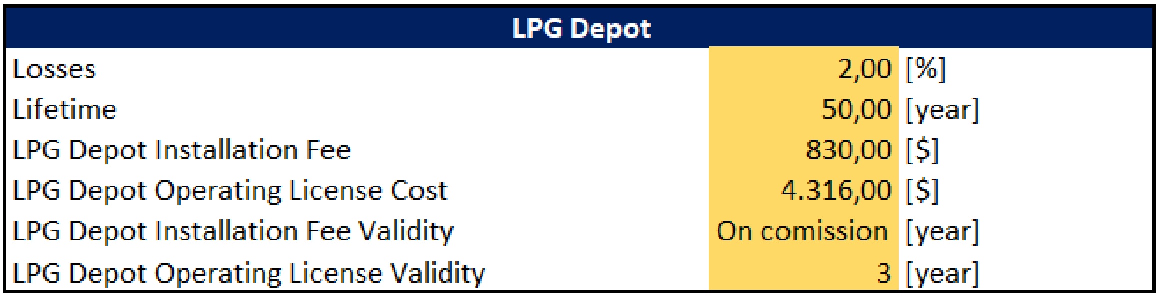
Botting Station		
Overnight cost	7.000.000,00	[$]
FOM	348.400,00	[$/year]
VOM	35,00	[$/ton]
Lifetime	20	[year]
Losses	2,00	[%]
Cylinder Requalification Cost	7,17	[$/cylinder]
Cylinder Requalification Validity	10	[year]
Bottling Station Installation Fee	830,00	[$]
Bottling Station Operating License Cost	4.316,00	[$]
Bottling Station Installation Fee Validity	On comission	[year]
Bottling Station Operating License Validity	3	[year]

Table 7. Model inputs: Bottling Station. Source: Own elaboration.



Bulk Transportation		
Capacity	24,00	[ton/vehicle]
Vehicle cost	200.380,79	[$]
Fuel consumption	34,50	[L/100km]
FOM	127,00	[% of VOM]
VOM	0,20	[$/km]
Lifetime	35	[year]
Losses	2,00	[%]
Bulk Transportation License Cost	456,50	[$]
Bult Transportation License Validity	5	[year]

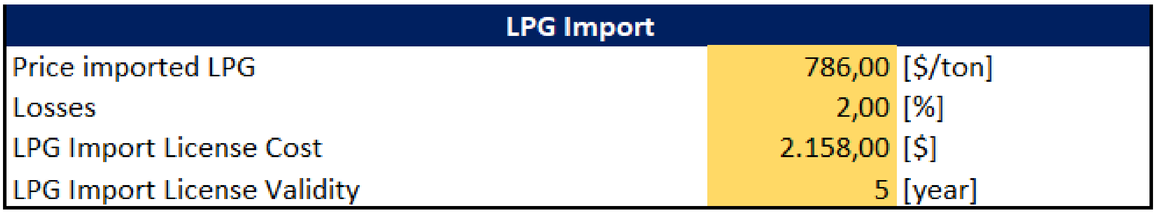
Table 8. Model inputs: Bulk Transportation. Source: Own elaboration.



LPG Depot		
Losses	2,00	[%]
Lifetime	50,00	[year]
LPG Depot Installation Fee	830,00	[$]
LPG Depot Operating License Cost	4.316,00	[$]
LPG Depot Installation Fee Validity	On comission	[year]
LPG Depot Operating License Validity	3	[year]

Table 9. Model inputs: LPG Depot. Source: Own elaboration.

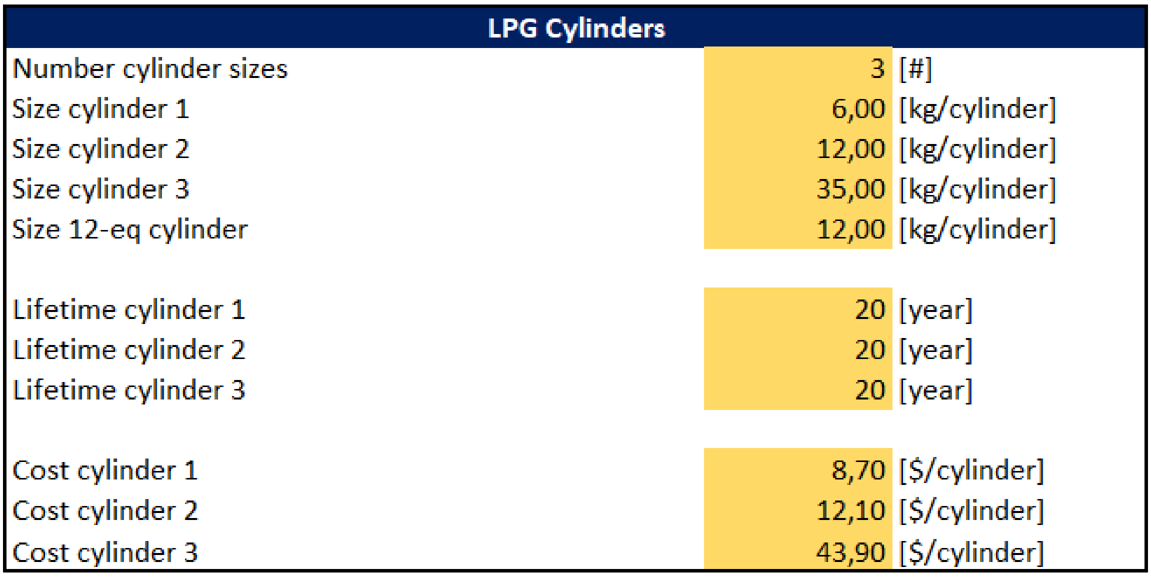
Additionally, Table 10 presents the inputs needed to calculate the importation costs.



LPG Import		
Price imported LPG	786,00	[$/ton]
Losses	2,00	[%]
LPG Import License Cost	2.158,00	[$]
LPG Import License Validity	5	[year]

Table 10. Model inputs: LPG Import. Source: Own elaboration.

Finally, since the model is able to take into account different cylinder sizes, the parameters needed in the calculations related are presented in Table 11.



LPG Cylinders		
Number cylinder sizes	3	[#]
Size cylinder 1	6,00	[kg/cylinder]
Size cylinder 2	12,00	[kg/cylinder]
Size cylinder 3	35,00	[kg/cylinder]
Size 12-eq cylinder	12,00	[kg/cylinder]
Lifetime cylinder 1	20	[year]
Lifetime cylinder 2	20	[year]
Lifetime cylinder 3	20	[year]
Cost cylinder 1	8,70	[$/cylinder]
Cost cylinder 2	12,10	[$/cylinder]
Cost cylinder 3	43,90	[$/cylinder]

Table 11. Model inputs: LPG Cylinders. Source: Own elaboration.

4.2 KIGALI CASE

In this case study, the focus is directed towards the intricate distribution dynamics of Liquified Petroleum Gas (LPG) within Kigali, the capital city of Rwanda. As previously elucidated, Kigali stands as one of the five provinces of the nation, holding not only its prominent status as the capital but also bearing the mantle of the highest existing and projected LPG consumption levels. This can be attributed to its substantial urban populace, which is a direct result of its standing as the nation's capital. Thus, the strategic choice of Kigali for our inaugural case study stems from its pivotal position for comprehensive analysis.

For this scenario, the LPG depot is situated in Rusororo, nestled within the Gasabo district of Kigali province. This strategic choice finds its roots in the existing geographical distribution of authentic depots within the region (Mangiri, 2023), ensuring a sense of congruence with the prevailing industry layout. To complement this, the bottling station and accompanying warehouse facilities find their integration within the Jabana district. This decision is grounded in the guidelines stipulated by Rwanda's LPG Master Plan

(GLPGP, 2020), which meticulously outlines recommendations for such placements to optimize the supply chain network.

Crucially, this comprehensive configuration takes into account the distribution of LPG consumption demand within Kigali. The demand cluster selected for analysis lies within the Kicukiro district. This choice resonates with the district's affluence within the province (Nzayirambaho et al., 2022), which in turn postulates that it is likely to emerge as one of the primary early adopters of LPG for their culinary requirements. This assumption is rooted in the district's economic robustness, thus positioning it as a forerunner in adopting cleaner and more efficient energy alternatives for cooking purposes.

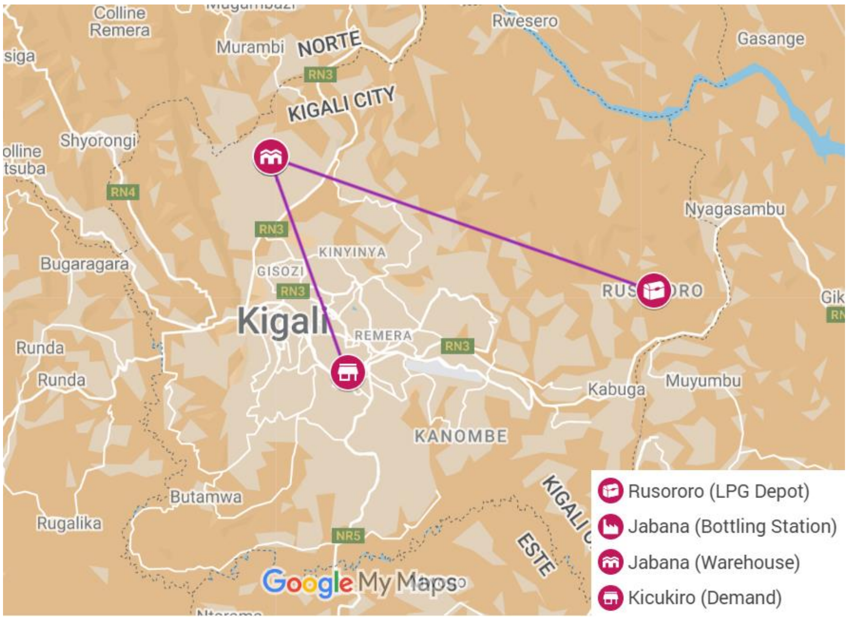


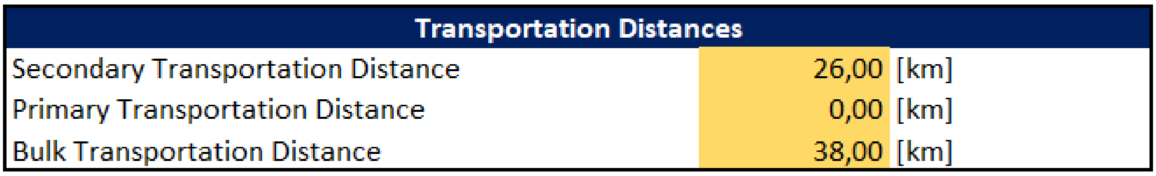
Figure 7. Map of Kigali Case. Source: Own elaboration.

A map of the locations previously detailed is presented in Figure 7. By dissecting the distribution model through the lens of Kigali, this case study endeavours to unravel the intricate balance between demand, infrastructure placement, and economic conditions. As we progress through subsequent case studies, we shall delve into divergent regional contexts, each presenting its own unique tapestry of challenges and opportunities within the LPG supply chain in Rwanda.

LPG Demand & Capacity		
LPG Demand	8.582,00	[ton]
LPG Total Demand (in LPG Depot)	80.086,00	[ton]
Bottling Station Capacity	30.465,00	[ton]

Table 12. Kigali Case: LPG Demand & Capacity. Source: Own elaboration.

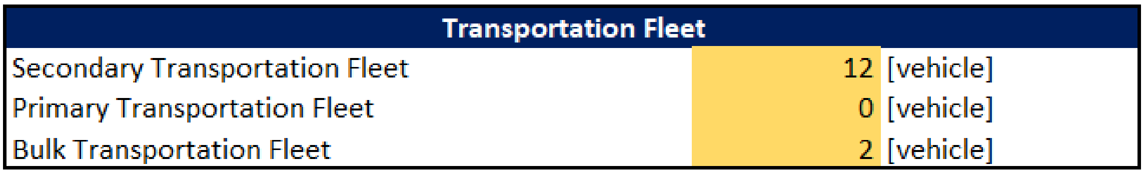
The input data related to the LPG Demand in this case is presented in Table 12. For the context of this case study, the demand projection for the city of Kigali stands at a substantial 30,465 tons. Furthermore, this demand value is strategically apportioned to the Kicukiro district, which accounts for 28.17% of the city's demand, as inferred from population metrics (Globalexpansion, n.d.). The holistic consideration of LPG supply necessitates the evaluation of the LPG depot's total demand and the bottling station's capacity. In the case of the LPG depot, it encompasses the overarching national demand, while the bottling station's capacity is tailored to cater exclusively to regions supplied by a particular station. For this scenario, the focus is solely on the city of Kigali province, aligning with the forecasts outlined in Rwanda's LPG Master Plan (GLPGP, 2020).



Transportation Distances		
Secondary Transportation Distance	26,00	[km]
Primary Transportation Distance	0,00	[km]
Bulk Transportation Distance	38,00	[km]

Table 13. Kigali Case: Transportation Distances. Source: Own elaboration.

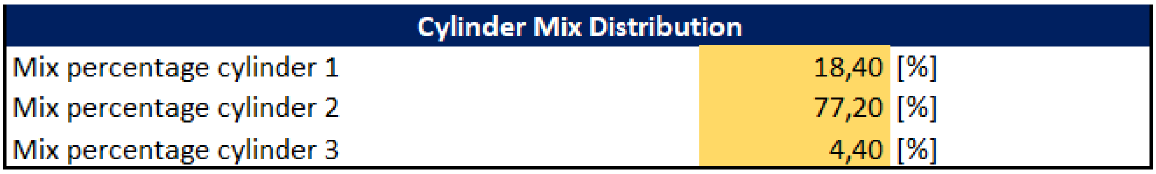
Table 13 provides a detailed overview of the transportation distances, meticulously obtained through the utilization of Google Maps to calculate road distances. The bulk transportation distance pertains to the expanse between the LPG depot's location and the bottling station. This distance encapsulates the span over which bulk quantities of LPG are transferred from the depot to the bottling station to initiate the subsequent stages of the supply chain. In contrast, the concept of primary transportation distance holds no relevance in this context, primarily due to the strategic integration of the warehouse within the confines of the bottling station itself. This symbiotic arrangement streamlines the logistical flow, rendering the primary transportation distance concept inconsequential for this scenario. Lastly, the secondary transportation distance revolves around the distance encompassing the movement of LPG from either the warehouse or the bottling station to the designated demand clusters.



Transportation Fleet		
Secondary Transportation Fleet	12	[vehicle]
Primary Transportation Fleet	0	[vehicle]
Bulk Transportation Fleet	2	[vehicle]

Table 14. Kigali Case: Transportation Fleet. Source: Own elaboration.

Table 14 offers a breakdown of the fleet composition, delineating the number of vehicles designated for each mode of transportation. This allocation has been calculated to optimize the frequency of trips, considering the working days within a year—a facet that will be expounded upon in a subsequent section. It is pertinent to highlight a notable feature of this allocation: the absence of primary transportation vehicles. This absence is a direct consequence of the integration of the warehouse within the precincts of the bottling station. This symbiotic arrangement, which streamlines logistical processes, obviates the requirement for distinct primary transportation vehicles in this particular case.



Cylinder Mix Distribution		
Mix percentage cylinder 1	18,40	[%]
Mix percentage cylinder 2	77,20	[%]
Mix percentage cylinder 3	4,40	[%]

Table 15. Kigali Case: Cylinder Mix Distribution. Source: Own elaboration

The cylinder mix distribution is presented in Table 15, it has been derived from the discerning insights unveiled within Rwanda's GLP Master Plan (GLPGP, 2020).

4.3 RUBAVU CASE

The focus in this case study is directed towards the distribution dynamics of Liquified Petroleum Gas (LPG) within the region of Gisenyi, the second-largest city in Rwanda, nestled within the Rubavu district. In contrast to the initial case, which focused on the distribution landscape of the capital city, this exploration aims to draw insightful comparisons with another significant urban centre, which is located in the Western province of the country.

For this scenario, the LPG depot will be positioned in Rusizi, a strategic decision taken by following the guidelines and recommendations provided within Rwanda's LPG Master Plan (GLPGP, 2020), which offers a prescriptive approach towards the optimal placement of some critical infrastructural elements.

Additionally, mirroring the approach taken in the preceding case, we will once again assume that, in this context, the bottling station and warehouse are co-located and seamlessly integrated in Kibuye, chosen for this purpose since it is the capital of the province, therefore it is reasonable to assume it as an appropriate location for industry placement.

The demand nucleus—consistent with our prior explanations—is strategically located within the Rubavu district. In Figure 8, all the locations previously stated are presented in a map.

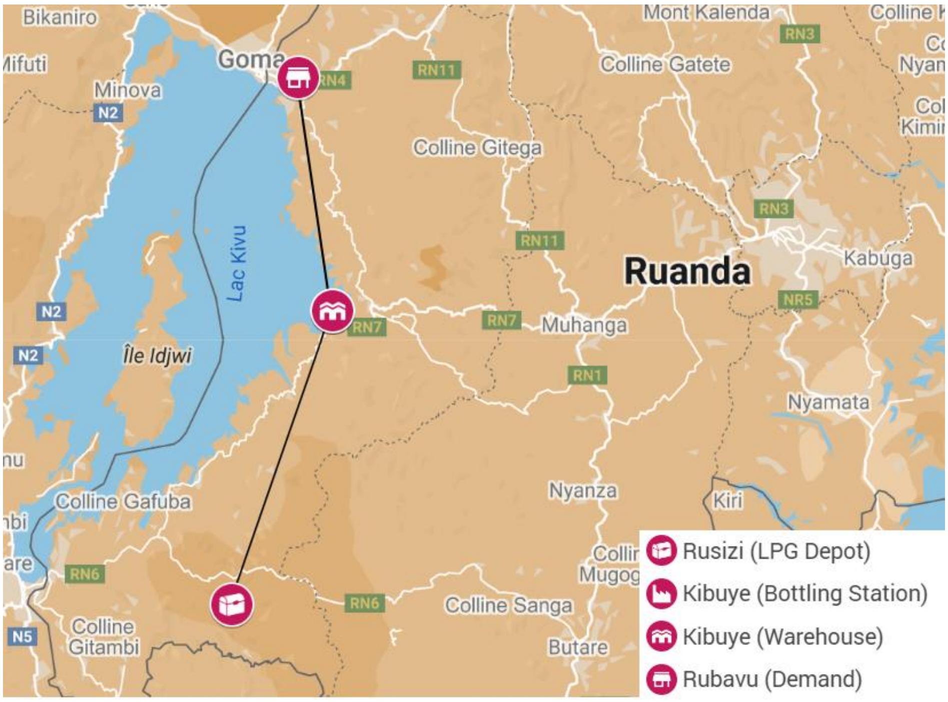


Figure 8. Map of the Rubavu Case. Source: Own elaboration.

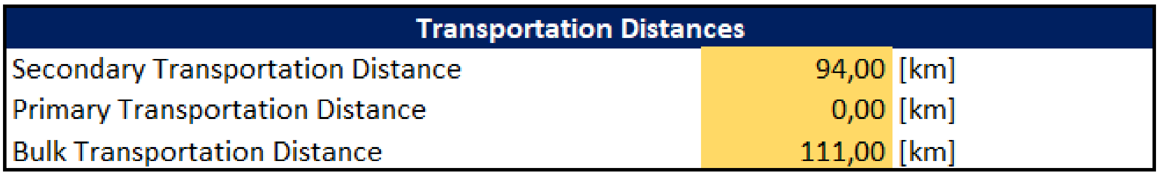
The dataset pertaining to LPG Demand for this specific case is presented in Table 16. In the context of this case study, the estimation of LPG demand for the Western province is noteworthy, amounting to a substantial 12,773 tons. Moreover, this demand projection has been judiciously apportioned to the Rubavu district, which accounts for 18.87% of the province's total demand. This allocation is drawn from demographic indicators (Globalexpansion, n.d.).

The comprehensive analysis of LPG supply mandates the examination of both the total demand at the LPG depot level and the capacity of the bottling station. Concerning the LPG depot, it encapsulates the aggregate national demand. Conversely, the capacity of the bottling station is configured to cater exclusively to the territories serviced by that particular station. In this scenario, the considered bottling station extends its supply reach to encompass both the Western and Southern provinces. This strategic alignment is congruent with the projections delineated within Rwanda's GLP Master Plan (GLPGP, 2020).

LPG Demand & Capacity		
LPG Demand	2.410,00	[ton]
LPG Total Demand (in LPG Depot)	80.086,00	[ton]
Bottling Station Capacity	24.260,00	[ton]

Table 16. Rubavu Case: LPG Demand & Capacity. Source: Own elaboration.

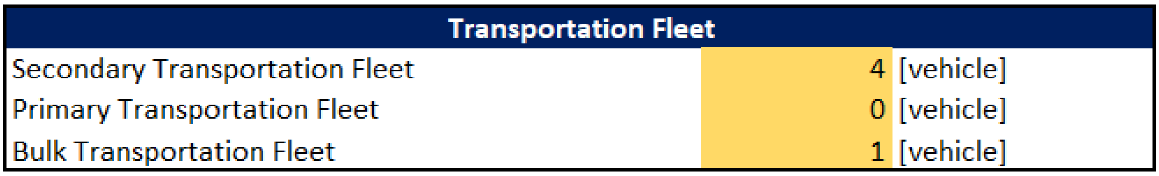
Mirroring Table 12, Table 17 provides a detailed overview of the transportation distances, obtained through the utilization of Google Maps to calculate road distances. Moreover, as happened in the previous case, primary transportation distance is not considered due to the warehouse being incorporated into the bottling station.



Transportation Distances		
Secondary Transportation Distance	94,00	[km]
Primary Transportation Distance	0,00	[km]
Bulk Transportation Distance	111,00	[km]

Table 17. Rubavu Case: Transportation Distances. Source: Own elaboration

Furthermore, Table 18 replicates Table 4 and offers a breakdown of the fleet composition, delineating the number of vehicles designated for each mode of transportation.



Transportation Fleet		
Secondary Transportation Fleet	4	[vehicle]
Primary Transportation Fleet	0	[vehicle]
Bulk Transportation Fleet	1	[vehicle]

Table 18. Rubavu Case: Transportation Fleet. Source: Own elaboration

The cylinder mix distribution is considered the same as in the previous case, presented in Table 15, based on the insights from Rwanda's GLP Master Plan (GLPGP, 2020).

4.4 NYARUGURU CASE

This case delves into the intricate distribution dynamics of Liquified Petroleum Gas (LPG) within a rural expanse. In line with this objective, the demand facet will be positioned within Nyaruguru, a district marked by lower population density, located in the southern province. Distinct from the preceding cases that centred on urban contexts, the subsequent cases will pivot towards the exploration of rural settings.

For this specific scenario, mirroring the methodology embraced in the prior instance, the LPG depot will find its strategic placement in Rusizi, situated within the Western province.

Furthermore, adhering to the same strategic approach utilized in the previous cases, we will reiterate the premise that, within this context, the bottling station and warehouse will be co-located. This integration is envisioned within Muhanga, a locale positioned within the Southern province, coinciding with the region under study for demand analysis. This strategic choice finds its moorings within the recommendations stipulated by Rwanda's LPG Master Plan (GLPGP, 2020), which imparts some guidance on the appropriate locations for such infrastructure.

As in continuity with previous explanations, the epicentre of demand—aligning with earlier discussions—is strategically sited within the Nyaruguru district. Figure 9 elucidates a visual representation of all the aforementioned locations, charted onto a map.

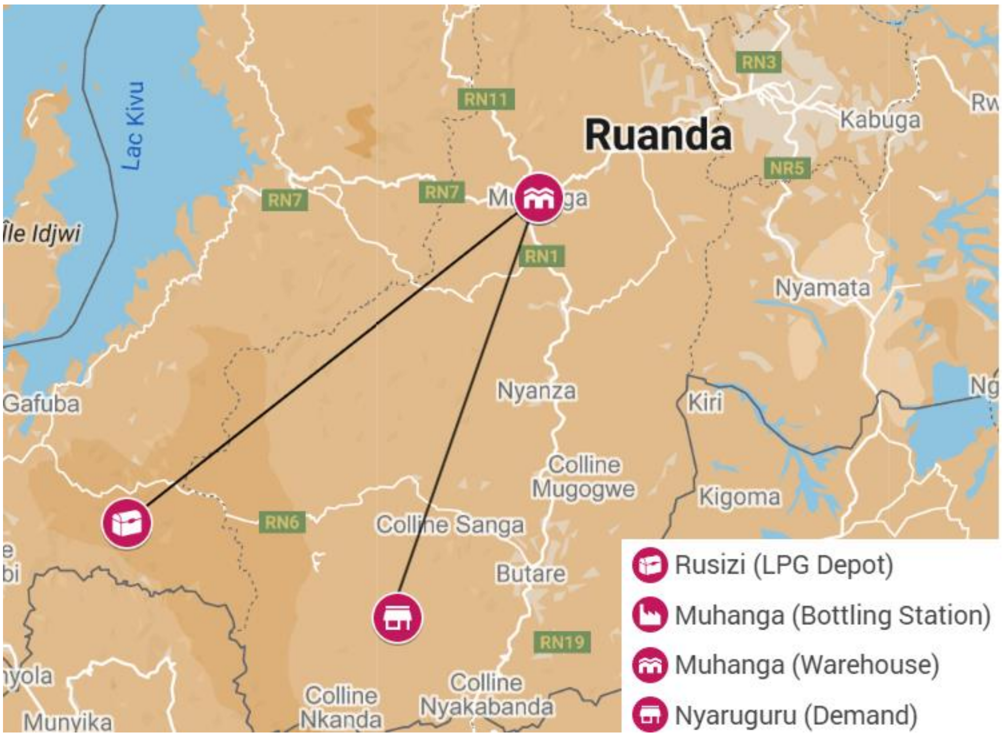


Figure 9. Mapo f the Nyaruguru Case. Source: Own elaboration.

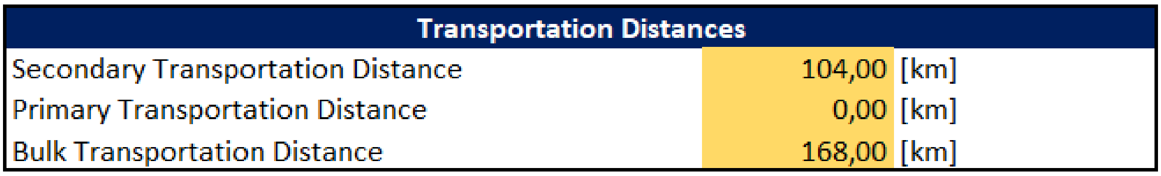
The dataset pertinent to LPG Demand within this particular case has been presented in Table 19. Within the context of this case study, the estimation of LPG demand within the Southern province amount to 11,487 tons. Furthermore, this demand projection has been meticulously allocated to the Nyaruguru district, constituting 10.60% of the province's aggregate demand. This allotment is inferred from demographic indicators (Globalexpansion, n.d.).

The comprehensive exploration of LPG supply necessitates the concurrent examination of both the total demand at the LPG depot level and the capacity of the bottling station. In relation to the LPG depot, it encapsulates the collective national demand. Conversely, the configuration of the bottling station's capacity is tailored exclusively to cater to the regions served by that particular station. In this scenario, the bottling station is assumed to exclusively serve the Southern province. This premise is grounded in a conjecture that posits the existence of at least one bottling station per province.

LPG Demand & Capacity		
LPG Demand	1.216,00	[ton]
LPG Total Demand (in LPG Depot)	80.086,00	[ton]
Bottling Station Capacity	11.487,00	[ton]

Table 19. Nyaruguru Case: LPG Demand & Capacity. Source: Own.

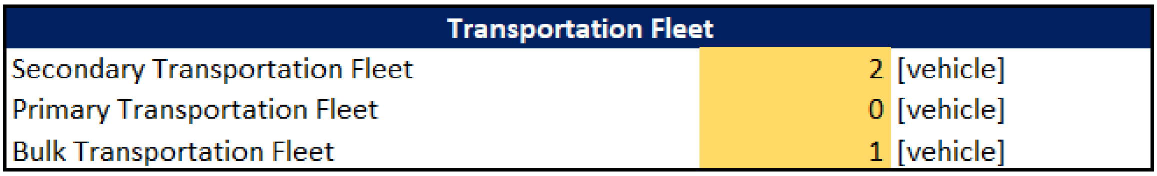
As explained in the previous cases, Table 20 provides a detailed overview of the transportation distances, obtained through the utilization of Google Maps to calculate road distances. Furthermore, as happened in the previous cases, primary transportation distance is not considered due to the warehouse being incorporated into the bottling station.



Transportation Distances		
Secondary Transportation Distance	104,00	[km]
Primary Transportation Distance	0,00	[km]
Bulk Transportation Distance	168,00	[km]

Table 20. Nyaruguru Case: Transportation Distances. Source: Own.

Furthermore, Table 21 replicates the previously presented cases and offers a breakdown of the fleet composition, delineating the number of vehicles designated for each mode of transportation with the same criteria exposed formerly.



Transportation Fleet		
Secondary Transportation Fleet	2	[vehicle]
Primary Transportation Fleet	0	[vehicle]
Bulk Transportation Fleet	1	[vehicle]

Table 21. Nyaruguru Case: Transportation Fleet. Source: Own.

The cylinder mix distribution is considered the same as in the previous case, presented in Table 15, based on the insights from Rwanda's GLP Master Plan (GLPGP, 2020).

4.5 NYARUGURU CASE (WAREHOUSE SCENARIO)

This final case centres on the identical demand cluster as its predecessor. However, a notable distinction emerges: whereas the antecedent cases involved the integration of the warehouse within the bottling station, this particular iteration introduces a noteworthy variation. The bottling station's location is envisioned within the Western region, akin to the context of the Rubavu case. In parallel, a standalone warehouse is proposed within the Southern province, intended to serve as a designated stockholding facility for that region.

This configuration, presented in Figure 10, serves multiple purposes, one of which involves the testing of a hypothesis delineated within Rwanda's LPG Master Plan (GLPGP, 2020). This hypothesis postulates that, in scenarios where the demand surpasses a specific threshold, one potential approach is to establish an independent bottling station within each province. Conversely, until that juncture, it may prove efficacious to consolidate the demands of two provinces under a single bottling station.

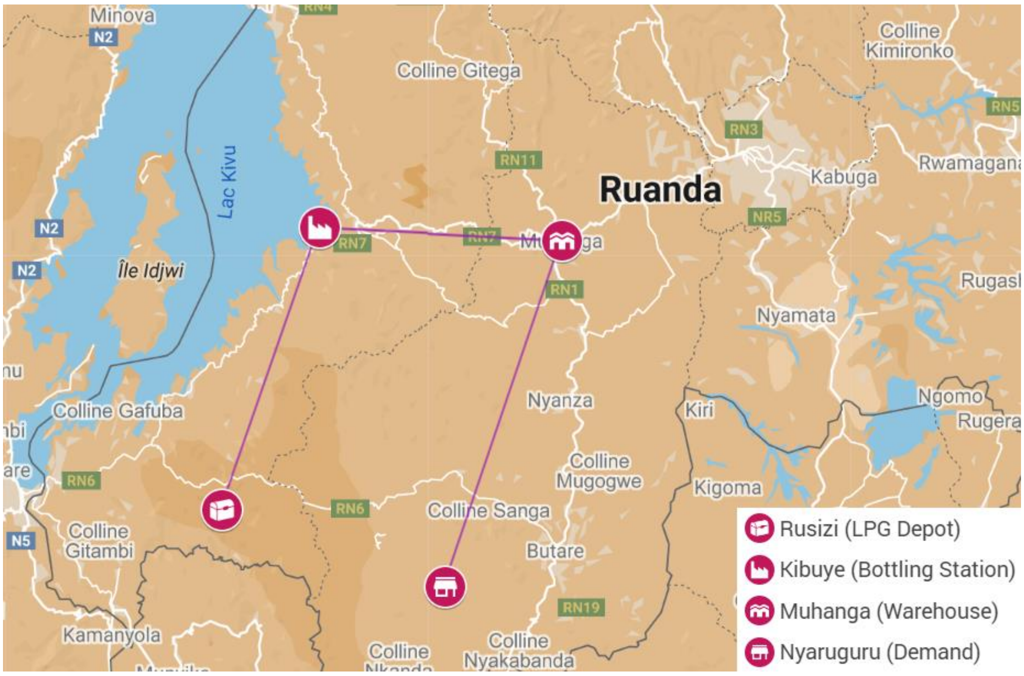


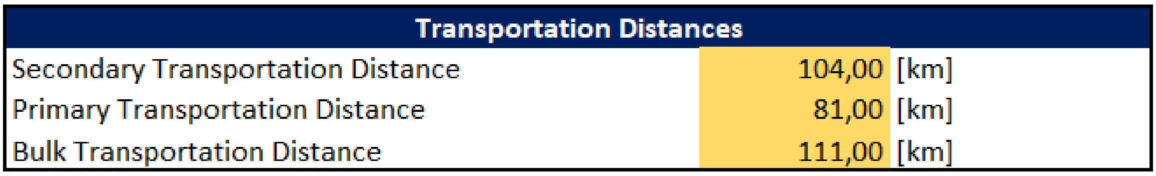
Figure 10. Map of Nyaruguru Case (WHS). Source: Own elaboration.

The dataset pertinent to LPG Demand within this particular case has been presented in Table 22. Within the context of this case study, the estimation of LPG demand for the Nyaruguru district is the same one as in the former case. Furthermore, the comprehensive exploration of LPG supply necessitates the concurrent examination of both the total demand at the LPG depot level and the capacity of the bottling station. In relation to the LPG depot, it is considered to encapsulate the collective national demand. Conversely, the configuration of the bottling station's capacity is tailored exclusively to cater to the regions served by that particular station. In this scenario, the bottling station is assumed to exclusively serve both the Western and Southern provinces.

LPG Demand & Capacity		
LPG Demand	1.216,00	[ton]
LPG Total Demand (in LPG Depot)	80.086,00	[ton]
Bottling Station Capacity	24.260,00	[ton]

Table 22. Nyaruguru Case (WHS): LPG Demand & Capacity. Source: Own elaboration.

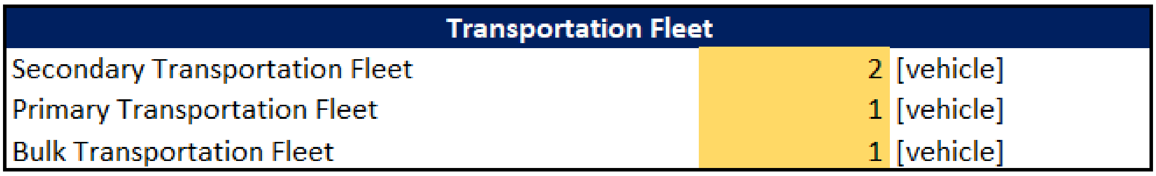
A significant point of distinction in Table 23 is that, unlike previous cases, the consideration of the primary transportation distance is introduced here. This variance arises due to the distinct arrangement where the bottling station and warehouse are not situated in the same location.



Transportation Distances		
Secondary Transportation Distance	104,00	[km]
Primary Transportation Distance	81,00	[km]
Bulk Transportation Distance	111,00	[km]

Table 23. Nyaruguru Case (WHS): Transportation Distances. Source: Own elaboration.

Furthermore, Table 24 replicates the previously presented cases and offers a breakdown of the fleet composition, delineating the number of vehicles designated for each mode of transportation with the same criteria exposed formerly. Since primary transportation is going to take place in this case, vehicles have been allocated to the fleet for this purpose, as opposed to the former scenarios.



Transportation Fleet		
Secondary Transportation Fleet	2	[vehicle]
Primary Transportation Fleet	1	[vehicle]
Bulk Transportation Fleet	1	[vehicle]

Table 24. Nyaruguru Case (WHS): Transportation Fleet. Source: Own elaboration..

The cylinder mix distribution is considered the same as in the previous cases, presented in Table 15, based on the insights from Rwanda's GLP Master Plan (GLPGP, 2020).

Capítulo 5. ANALYSIS OF THE RESULTS

After the data for each case was obtained and presented in the previous section, the results for each of the four major cost categories are shown below in Figure 11.

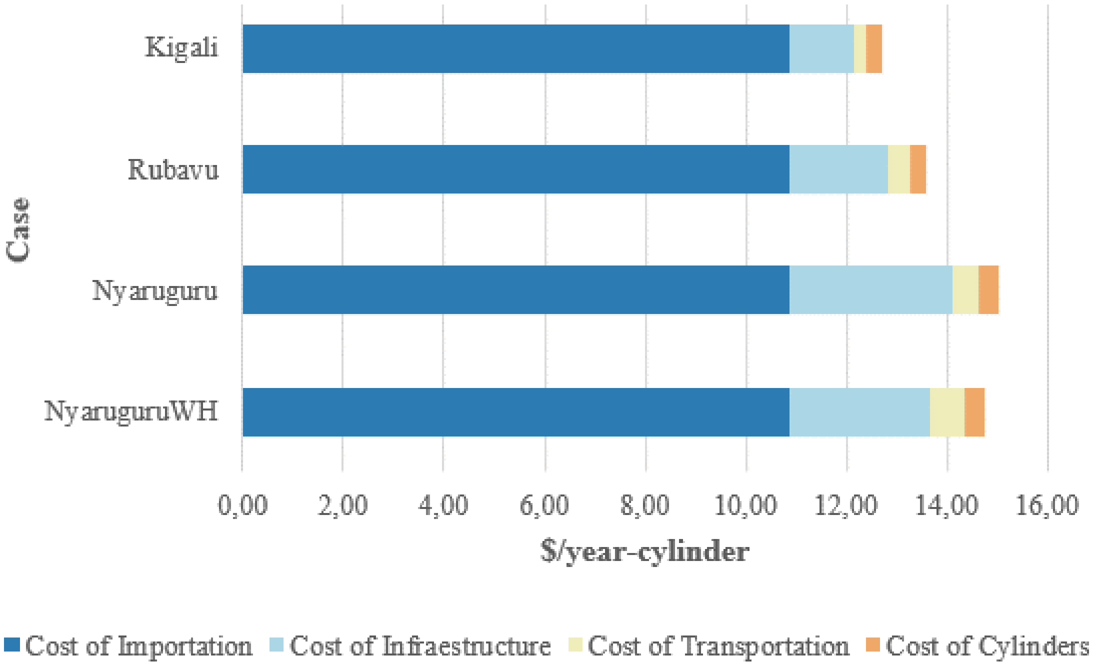


Figure 11. Cost breakdown comparative for each case.[3] *Source: Own elaboration.*

As a result of the model complexity, several conclusions can be made regarding Rwanda's LPG distribution network. Therefore, in order to perform a detailed analysis, each cost will be discussed individually as well as the inputs which impact it and possible alternatives to reduce it. This methodology is aimed at obtaining a comprehensive review of the model.

Chief among these insights is the relevance of the LPG importation cost within the overall cost structure. This cost amounts to USD10.87 per cylinder-year, being fixed independently of the case analyzed. Furthermore, this cost is can only be affected lightly

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[3] USD/EUR = 0.92 [Date: 08/21/2023]

by internal legislation, as it is largely dependent on the negotiations with the supplying states and highlights the importance of obtaining a favorable price.

Moreover, the cost of cylinders emerges as a variable cost component closely linked with the turnover rate. And therefore, LPG demand. This effect manifests primarily in urban demand hubs where the higher turnover rates result in a cylinder cost of USD0.32 per cylinder-year. On the other hand, rural environments, present a slight increase up to USD0.37 per cylinder-year. The difference in costs promotes the use of optimization methodologies based around inventory management strategies to mitigate overstocking of LPG and thus improving the turnover rate.

Infrastructure and transportation costs, on the other hand, exhibit significant variability across the studied scenarios. This variability reflects the various interdependencies and synergies between regional characteristics, population density, and the efficient utilization of transportation and storage infrastructure. Also, these correlations suggest that regions with higher demand and concentrated population will present a higher utilization of the required infrastructure, resulting in lower per cylinder costs.

Moving into rural contexts, a clear trend emerges where rural scenarios carry higher costs compared to urban ones. This difference can be chalked up to the practical challenges of reaching widely scattered populations over long distances, leading to the need for more resource-intensive transportation methods. These findings practically highlight the necessity of crafting specific strategies that tackle the distinct hurdles posed by rural distribution networks.

A notable highlight comes from assessing Nyaruguru's demand scenarios. Here, we observe a significant cost reduction between the third and fourth cases. This reduction owes itself to a clever restructuring of the distribution network. Specifically, setting up a bottling plant for the southern and western provinces, along with a dedicated warehouse for southern province demand storage, results in a remarkable 27.65% cut in costs linked to the analyzed demand. The reason behind it resides in the allocation of infrastructure’s fixed costs. In the third case, when the bottling station and the warehouse are integrated and the plant only fills the cylinders needed for the southern province, all the fixed costs of said infrastructure are allocated to the case. However, in the last scenario, when the bottling station fills the cylinders for both the southern and the western region, the fixed costs of the bottling station are allocated proportionally between said demands, therefore, the southern region bears a smaller fraction of the costs. This example serves to vividly showcase the real benefits that come with thoughtfully optimizing the network for the demand.

A detailed cost breakdown by case is included in Annex 1. In it a more detailed breakdown of all costs for each of the proposed scenarios can be consulted. It contains the values for different calculated elements, that have been obtained following the methodology and order previously explained in the model description.

Capítulo 6. CONCLUSION & FUTURE WORK

6.1 CONCLUSION

The examination of the model's details has revealed some important insights about Rwanda's future LPG distribution network. By looking closely at the costs involved, several valuable takeaways that offer useful information for those involved in decision-making can be found.

One major finding is the impact of the LPG importation costs. These costs, which stay constant through the cases, plays a big role. While these can't be impacted internally, negotiating with the countries that supply the LPG could make a difference in managing these expenses.

Another impact is how cylinder costs change depending on their turnover. In dense city areas, where the cylinders see more frequent use, the costs are reduced. But in more rural places where the cylinder turnover is lower, the costs go increase slightly. This suggests that a cylinder management system could reduce the cost.

Looking at infrastructure and transportation costs, these vary based on the case studied. These are impacted by the total population within an area as well as infrastructure usage. Regions with a higher demand and a larger population will result in lower costs for each cylinder.

Focusing on rural areas, these tend to have higher costs compared to urban environments. This is due to the fact that population density is lower and therefore distribution costs are larger. This highlights the need to create a detailed plan to tackle rural implementation.

Focusing on the Nyaruguru cases, there's a big drop in costs between two situations, caused by the implementation of a warehouse within the area. By modelling an independent warehouse, costs dropped considerably.

6.2 FUTURE WORK

While the cost model for the LPG supply chain in Rwanda has proven valuable, it's crucial to acknowledge its inherent simplifications. These simplifications were necessary to create a practical analytical framework, but they also present opportunities for further research to enhance the model's accuracy and applicability.

Looking forward, several avenues for future research can be explored to refine and expand the cost model. Among them is the integration of accurate road network data using Geographic Information Systems (GIS). Also, exploring dynamic demand modeling could be valuable. This approach would account for fluctuations in demand over time due to factors like seasonal changes, economic shifts, and evolving consumer preferences. Furthermore, the model could be expanded to incorporate alternative transportation methods, and regional Fuel Price Analysis. Moreover, reverse logistics and inventory management techniques could be incorporated into the model to increase its accuracy and better reflect the actual procurement and operational costs.

Ultimately, ongoing research contributes to the effective distribution of LPG across Rwanda, advancing its energy goals and benefiting its population.

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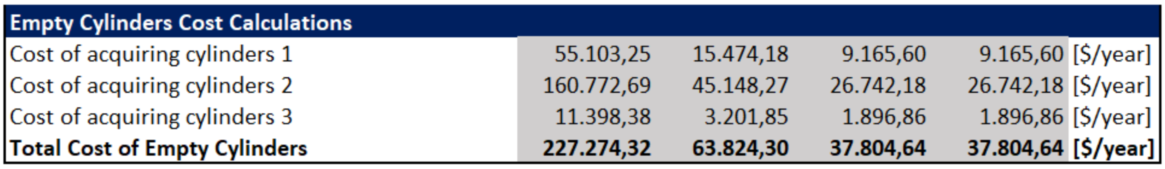
ANNEX I: COST BREAKDOWN BY CASE

Cost Calculations					
Secondary Transportation Cost Calculations					
Vehicle Cost	77.349,61	21.721,34	10.959,81	10.959,81	[$/year]
Fuel Consumption	17.177,27	17.439,63	9.735,52	9.735,52	[$/year]
FOM	17.682,36	15.124,22	8.520,04	8.520,04	[$/year]
VOM	14.094,03	14.309,29	7.988,04	7.988,04	[$/year]
Secondary Transportation License	95,68	80,60	81,34	81,34	[$/year]
Total Cost Secondary Transportation	**126.398,94**	**68.675,08**	**37.284,75**	**37.284,75**	**[$/year]**
Primary Transportation Cost Calculations					
Vehicle Cost	0,00	0,00	0,00	7.508,89	[$/year]
Fuel Consumption	0,00	0,00	0,00	7.273,07	[$/year]
FOM	0,00	0,00	0,00	3.056,20	[$/year]
VOM	0,00	0,00	0,00	4.245,06	[$/year]
Primary Transportation License	0,00	0,00	0,00	54,90	[$/year]
Total Cost Primary Transportation	**0,00**	**0,00**	**0,00**	**22.138,11**	**[$/year]**
Bulk Transportation Cost Calculations					
Vehicle Cost	13.907,60	3.905,54	1.970,59	1.970,59	[$/year]
Fuel Consumption	13.344,10	10.946,05	8.359,11	5.522,98	[$/year]
FOM	6.715,61	3.093,94	1.192,15	787,67	[$/year]
VOM	6.095,37	4.999,98	3.818,31	2.522,81	[$/year]
Bulk LPG Transportation License	84,02	47,19	23,81	23,81	[$/year]
Total Cost Bulk Transportation	**40.146,70**	**22.992,69**	**15.363,97**	**10.827,87**	**[$/year]**

Warehouse Cost Calculations					
Overnight cost	4.593,05	4.593,05	4.593,05	4.593,05	[$/year]
FOM	154.800,00	154.800,00	154.800,00	154.800,00	[$/year]
VOM	0,00	0,00	0,00	0,00	[$/year]
Warehouse Wholesale License	193,70	193,70	193,70	193,70	[$/year]
Total Cost Warehouse	**159.586,75**	**159.586,75**	**159.586,75**	**159.586,75**	**[$/year]**
Bottling Station Cost Calculations					
Overnight cost	130.745,04	46.106,71	49.132,05	23.263,80	[$/year]
FOM	106.404,79	37.523,22	39.985,34	18.932,88	[$/year]
VOM	325.650,88	91.449,38	46.142,10	46.142,10	[$/year]
Cylinder Requalification Cost	212.860,93	59.776,02	35.406,50	35.406,50	[$/year]
BS Installation Fee	15,50	5,47	5,83	2,76	[$/year]
BS Operation License	457,07	161,19	171,76	81,33	[$/year]
Total Cost Bottling Station	**776.134,22**	**235.021,98**	**170.843,57**	**123.829,36**	**[$/year]**
LPG Depot Cost Calculations					
LPG Depot Installation Fee	3,20	0,90	0,45	0,45	[$/year]
LPG Depot Operation License	181,04	50,84	25,65	25,65	[$/year]
Total Cost Depot	**184,24**	**51,74**	**26,10**	**26,10**	**[$/year]**

LPG Import Cost Calculations					
LPG Import Cost	7.770.134,32	2.182.011,62	1.100.965,20	1.100.965,20	[$/year]
LPG Import License	457,84	457,84	457,84	457,84	[$/year]
Total Cost LPG Import	**7.770.592,16**	**2.182.469,46**	**1.101.423,04**	**1.101.423,04**	**[$/year]**



Empty Cylinders Cost Calculations					
Cost of acquiring cylinders 1	55.103,25	15.474,18	9.165,60	9.165,60	[$/year]
Cost of acquiring cylinders 2	160.772,69	45.148,27	26.742,18	26.742,18	[$/year]
Cost of acquiring cylinders 3	11.398,38	3.201,85	1.896,86	1.896,86	[$/year]
Total Cost of Empty Cylinders	**227.274,32**	**63.824,30**	**37.804,64**	**37.804,64**	**[$/year]**

ANNEX II: SDG ALIGNMENT

Throughout this document, the project's central objective was to model the Liquified Petroleum Gas (LPG) supply chain within Rwanda's LPG distribution network. This modeling aimed to facilitate access to clean cooking fuels, a pivotal endeavor in a region where an estimated 984 million individuals lack access to clean cooking facilities (IEA, n.d.). This pressing challenge underscores the critical importance of promoting efficient and sustainable cooking alternatives.

In 2016, Rwanda ratified the Paris Agreement, thereby committing to the pursuit of the Sustainable Development Goals (SDGs) outlined within it. This project emerges as a meaningful alignment with Rwanda's commitment to these global objectives, particularly contributing to the following key SDGs:

The heart of the project lies in the creation of a comprehensive tool designed to analyze the cost implications of the LPG supply chain. This tool's development and application hold paramount significance, especially in regions like Rwanda, where access to clean cooking fuels directly impacts public health, environmental conservation, and economic development.

The project's alignment with SDG 7: Affordable and Clean Energy (SGDS, n.d.) is evident as the tool's focus on cost analysis directly contributes to enhancing the affordability of clean cooking fuels. SDG 9: Industry, Innovation, and Infrastructure (SGDS, n.d.) also resonates, as the tool aids in creating efficient and sustainable infrastructure within the LPG distribution network. Finally, the project strongly resonates with SDG 3: Good health and well-being (SGDS, n.d.), since one of the main purposes of the transition towards cleaner cooking technologies and fuels is to minimize the home air pollution caused by certain fuels when cooking, which has a severe impact in millions of people, especially women and children in developing nations.

In conclusion, this project's synergy with the Sustainable Development Goals exemplifies its profound relevance to Rwanda's societal and environmental aspirations. By addressing the critical need for clean cooking fuels and emphasizing the development of a sophisticated cost analysis tool, the project paves the way for accessible, affordable, and sustainable solutions that transcend beyond environmental benefits and contribute to comprehensive national development.