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Rural electrification as multi-sectoral coevolution: The geography of electricity and dairy sector development in Rwanda

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ABSTRACT

Research on multisectoral interactions is gaining attention for its potential to address global challenges, including climate change, food security, and energy access. These dynamics are especially relevant in sub-Saharan Africa, where expanding energy access is a key policy goal. This study contributes to the literature on sectoral coevolution with a case from a novel geographical and sectoral context. Drawing on economic geography and energy and development studies, it applies a spatial lens to the interactions between an expanding electricity sector and the dairy value chain (DVC), through a comparative case study of four districts in north-western Rwanda. Results show that both sectors have expanded geographically and reinforced one another, mainly through alignment with national policies. A network of DVC and electricity actors mediates this coevolution. However, challenges such as unreliable electricity, high costs, poor maintenance, milk shortages, and uneven adoption of internet and communication technologies (ICT) constrain this potential. From a geographical perspective, the study shows how sectoral coevolution reshapes rural–urban linkages through socio-material flows. It highlights how the expansion of electricity and dairy networks co-produces new proximities and geographies of rural transformation. Harnessing this coevolution to alleviate poverty requires further support for farmers' modern milk production technologies, improved ICT integration, and more reliable, affordable electricity.

1. Introduction

To address complex global challenges such as climate change, food security, and energy access, Sustainability Transitions (ST) researchers are increasingly analysing interactions across multiple sectors and technologies (Andersen & Markard, 2020; Breitschopf et al., 2023; Markard & Hoffmann, 2016). This multi-sectoral approach responds to critiques of the field's traditional focus on single-sector transitions, which can obscure cross-sector interdependencies and broader industrial transformations (Markard, 2018). In this context, sectors are seen as networks of actors who collaborate and compete. These actors share knowledge bases, production processes, and technologies (Andersen et al., 2020). While intra-sector networks remain important, a multi-sectoral perspective is emerging. It highlights that transformation in a focal sector often relies on changes in supporting sectors. These sectors provide essential knowledge, technologies, and resources (Mäkitie et al., 2022).

This sectoral interdependence is particularly relevant to energy transitions in sub-Saharan Africa (SSA), where expanding electricity access is a key development priority. Unlike OECD (Organisation for Economic Co-operation and Development) countries, where the focus is on decarbonising the mature electricity systems and managing household demand, SSA countries are working to extend basic electricity services to underserved populations (Hodok & Kozluk, 2024). Despite these differences, both regions face similar challenges in meeting the growing electricity demand. However, the scalar dynamics and societal context of this transition differ, with a focus on rural industries in SSA versus transport and heavy industry in the OECD countries. As the electricity sector evolves in both contexts, emerging usage patterns are reshaping grid dynamics, while regulatory developments in adjacent sectors increasingly influence the pace and direction of energy transitions.

ST scholars argue that changes or reconfigurations in one sector often require resources (skills and assets) from other sectors to build or

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reconfigure a value chain (VC) (Andersen et al., 2020). A VC is here understood as a connected system encompassing activities such as the development, manufacturing, and distribution of specific technologies or products, their diffusion to the market, and their consumption (Fabio et al., 2025; Hoicka et al., 2025). Further, innovation processes to develop new or incrementally improve existing technologies in one sector involve the reorganisation of production and use that commonly involve multi-sectoral interactions that, in turn, contribute to the performance of those sectors and, thus, to industrial transformation (Breitschopf et al., 2023).

This study, situated in the ST field, contributes to the growing literature on sectoral coevolution by studying it through a spatial lens, operationalised through the concepts of location, flow, and scale. Moving beyond a single-sector approach, it explores how electricity, as a catalyst for economic development, interacts with other sectors to drive rural transformation. Using a comparative case study design, we examine the coevolution of Rwanda's electricity subsector and the dairy value chain (DVC) in agriculture from 2005 to 2023. The study draws on two key bodies of literature in addition to multi-sectoral coevolution, namely:1) Economic Geography; and 2) energy and development research in SSA where existing literature on emerging energy geographies (Ahlborg, 2018; Hategekimana et al., 2025), energy transitions (Bhamidipati et al., 2019; Ockwell & Byrne, 2016), and productive uses of electricity (Ngowi et al., 2019; Wassie & Ahlgren, 2023) inform our analysis of cross-sectoral coevolution.

The study is the first to apply a multi-sectoral perspective on the interaction between electricity and the dairy industry. It contributes to the theorisation within ST by examining the coevolution between two sectors that are expanding both in geographical and structural terms, which is different from the existing case studies on the topic, predominantly from high-income countries and well-established regimes (Berlo et al., 2017; Fuenfschilling & Truffer, 2014; Geels, 2014). The Rwandan electricity sector is characterised by a fragmented service regime and rapid transformation during the study period (Hategekimana et al., 2025), which can also be said for the DVC. Given the fast-paced and ambitious development agenda that the government is pursuing, Rwanda presents an interesting case for analysing and contextualising the spatiality of multi-sector transformation (Unsworth et al., 2025). Rwanda has made rapid progress in electrifying its population. From 2011 to 2022, the electricity access rate increased from 10% to 50% (Mugyenyi et al., 2025). There is also a policy push (e.g. the Made in Rwanda campaign and Vision 2050) (Ministry of Finance and Economic Planning, 2020) to develop the domestic DVC as a critical component of economic transformation strategies (Behuria, 2018; Habiyaremye et al., 2021).

At the same time, a rapid sectoral transformation is underway, yet traditional energy systems and dairy value chains (DVCs) based on informal marketing channels persist (Habiyaremye et al., 2023). These channels are characterised by unorganised, unregistered, or weakly regulated systems through which raw, boiled, or pasteurised milk bypasses formal quality control and industrial processing. Instead, milk is sold directly to consumers through door-to-door delivery, street vendors, corner shops, and canteens (Habiyaremye et al., 2021, 2023). Such systems remain widespread across the East African Community (EAC)[1] countries (Abdulsamad & Gereffi, 2016). In Kenya, informal milk marketing is considered illegal and subject to penalties (Blackmore et al., 2022). In contrast, in Rwanda and Uganda, it functions as an alternative system operating largely outside formal milk-handling, processing, and marketing structures, which should be integrated into formal marketing (Habiyaremye et al., 2023; Majalija et al., 2020). The persistence of these networks is linked to the long distances between farmers and Milk Collection Centres (MCCs), established relationships among farmers, milk traders, and consumers, and the limited coverage of MCCs' infrastructure (Habiyaremye et al., 2023).

To the field of economic geography, the analysis contributes a relevant example of how electricity and the DVC develop spatially with new locations added to the VC, but also changing relational proximity as electricity and milk enable one another to flow alongside technologies, knowledge, money, and dairy products between countryside and city in the country and the region (Behuria, 2018). This is the first study from the East African region, and specifically Rwanda, to explore sectoral coevolution through a spatial lens. This contrasts with prior research that has examined other dimensions, such as the political economy of Rwanda's energy transition (Rodríguez-Manotas et al., 2018; van der Straeten, 2021), the development of the dairy sector (Abdulsamad & Gereffi, 2016; Habiyaremye et al., 2021), and broader energy and development frameworks (Lenz et al., 2017), which have not explicitly engaged with spatial dynamics. The study also demonstrates how the geographical and institutional contexts enable or hamper this coevolutionary dynamic.

Finally, the study builds on and contributes to energy and development studies that have established the interdependence between electrification and economic development. Here, studies analyse electrification and rural development dynamics as sociotechnical systems (Baptista & Plananska, 2017; Ockwell & Byrne, 2016; Riva et al., 2018) and interdependent processes characterised by diverse interactions and feedback loops (Colombo et al., 2018; Riva et al., 2018). However, energy and development studies are largely single-sector studies that unpack the electricity sector while black-boxing other VCs as "load", "demand," or "productive uses", with limited attention to the dynamics within these sectors (Domegni & Azouma, 2022; Hartvigsson et al., 2021). In contrast, this study contributes an analysis centred on sector *interfaces and interactions.* It unpacks the geographical and sociomaterial structures of the DVC and examines how it is affected by, and affects, changes in the electricity sector.

The article is organised as follows: The second section presents the theoretical perspectives that have informed the research design and analysis, as well as a summary of previous studies on the electrification of DVCs. Based on this, the analytical framework is presented. Section three presents the methodology. It includes data collection techniques, qualitative and quantitative methods, and accounts for the analysis done, and the geographical context on the coevolution of the electricity and the DVC sectors. The fourth section presents the results, including the geographical expansion of the electricity and dairy sectors, as well as the resulting interactions between the two sectors. The fifth section discusses the sustainability of the coevolution between the electricity sector and the DVC, and the sixth presents the conclusions and policy recommendations.

2. Theoretical perspectives and previous studies on electricity-dairy sector interactions

This study builds on economic geography perspective to understand multi-sectoral interactions. It also draws insights from existing literature in the ST field to understand multi-sectoral coevolution. Drawing on energy and development studies from Africa, the study builds on previous insights into complementary investments and findings specific to interactions between the electricity and dairy sectors.

2.1. An economic geography perspective on multi-sectoral interactions

The integration of evolutionary economic geography (EEG) with the ST field has provided valuable tools for understanding the spatial dynamics of sectoral transformation, specifically, how structural components of a sector or sociotechnical system (e.g., technologies, actors, institutions, infrastructures, and natural elements) are spatially reconfigured and interact across locations (Coenen et al., 2012; Hansen &

[1] East African Community is a regional integration bloc comprising eight member countries: Burundi, the Democratic Republic of Congo, Kenya, Rwanda, Somalia, South Sudan, Tanzania, and Uganda.

Coenen, 2015; Jedelhauser & Binder, 2018). Focusing on the energy sector, Bridge et al. (2013) emphasise the spatial restructuring of VCs linking urban demand centres to rural energy production sites.

This study applies the geographical concepts of location, flows, and scale. Absolute location refers to specific geographic sites involved in emerging VCs, while relative location and proximity capture evolving relationships between these sites, shaped by changing flows that connect distant places (Jedelhauser & Binder, 2018). For example, research on the coevolution of electric vehicles, battery charging, and smart grids shows how invention cities are becoming central nodes in global networks that link local production with global technological and knowledge hubs (Ferloni, 2022). Flows describe the movement of resources, technologies, knowledge, information, and finance across locations, evolving as sectors expand, contract, or reconfigure their VCs (Jedelhauser & Binder, 2018).

These flows also have scale dimensions that depend on the direction of the VCs. Economic geography studies show that some transitions in agri-value chains are oriented toward integration into global production networks. In such cases, they attract transnational flows of capital through Foreign Direct Investment (FDI), along with technology, standards, and institutional changes (Antràs & De Gortari, 2020; Kano et al., 2020). This process alters the location and stages of the VC as goods are increasingly processed in the Global South and exported to the Global North, reshaping cross-scale linkages. Conversely, other transitions focus on domestic markets through import substitution, creating local and regional complementarities and tensions (Barrett et al., 2019; Reardon & Minten, 2021).

2.2. Multi-sectoral interaction and coevolution in Sustainability Transitions

In the ST field, coevolution is a key concept that explains how sector change depends on the mutual influence and adaptation of the socio-material structure among multiple sectors (or socio-technical systems), or between a focal sector and its context. Co-evolution, originating from Darwin's theory, was initially applied to socio-technical systems to explain the mutual adaptation between industries and their environments (Costa & Horn, 2021). The analytical framing influences what interactions are in focus. Still, the multi-sectoral perspective emphasises that long-term transformation processes occur as socio-technical systems or sectors evolve through mutual influence or complementarities, which change over time (Andersen et al., 2024; Köhler et al., 2019; Mäkitie et al., 2022). The nature of multi-sectoral coevolution is thus understood as bidirectional, where changes driven by policy adjustments or technological change in one sector stimulate developments in another. This dynamic relationship reconfigures technological VCs, enhancing their performance (Mäkitie et al., 2022). As the VC spans multiple places, a coevolutionary perspective can also help embed institutional, technological, and geographical dimensions (Teufel et al., 2019).

So far, ST research on multi-sectoral interactions primarily draws on two perspectives. Institutional economics emphasises the coevolution of sectors with institutions and practices, where formal rules, such as policies, standards, and subsidies, shape what is permissible (Geels, 2004; Nonnenmacher, 2013). Evolutionary economics, on the other hand, emphasises sectoral adaptability through changes in capabilities and routines. It views sectors as evolving via experimentation and mutual influence, exchanging resources, competencies, and knowledge (Andersen et al., 2024). These exchanges typically lead to incremental changes and new socio-material configurations (Costa & Horn, 2021). Such interactions support the diffusion of new technologies and market dynamics, as seen in the integration of internet and communication technologies (ICT) in the coevolution of batteries and electric vehicles (Ferloni, 2022; Löhr & Chlebna, 2023).

In relation to the field’s central frameworks, such as the Multi-Level Perspective (MLP) that serves as a theoretical basis for understanding interactions within sociotechnical systems, Breitschopf et al. (2023) emphasise the importance of including cross-sectoral interactions and their potential impacts to expand this framework. They propose that such interactions occur at interfaces, which integrate shared elements such as actors, institutions, infrastructures, technology, resources, and knowledge. Related to Technological Innovation Systems (TIS), researchers have advanced the understanding of intersectoral interactions using concepts such as functional and structural couplings (Mäkitie et al., 2022). Functional couplings refer to input-output or supplier-buyer relationships, often forming a technological VC (Bento et al., 2021) and appearing as socio-material flows between sectors. Structural couplings, by contrast, involve shared infrastructure, actors, or resources. These couplings are relevant from a VC perspective. For instance, interactions among the agriculture, food, energy, and transport sectors illustrate how they couple around feedstock supply to produce green fuels for maritime transport (Urban et al., 2024). Spatial convergence, both local (e.g., community initiatives, housing policies) and global (e.g., blockchain technology), also shapes TIS interactions. Such convergence enables new technological and market dynamics, as seen in innovations like blockchain-based electricity trading (Hojckova et al., 2020).

Recent policy-oriented frameworks and empirical studies in the ST field emphasise multi-sectoral interactions, particularly the feedback between policy instruments and socio-technical system changes. These interactions suggest that policies and politics are key drivers of sustainability transitions (Edmondson et al., 2019). Reconfigured socio-technical systems reflect shifts in policy vision, resource allocation, taxation, and support mechanisms (Gong & Hansen, 2023).

Case studies also highlight synergies between electricity and sectors such as ICT (Andersen et al., 2020; Hiteva, 2021; Mori, 2020; Watson, 2019). Electricity-driven innovations in ICT enable new data connectivity and analytics, reshaping the VC of electricity (Gustafsson, 2017; Hiteva, 2021). Interfaces, such as smart meters and blockchains, facilitate integration by introducing new structural components and information flows, thereby enhancing intersectoral connectivity and efficiency (Teufel et al., 2019). Thus, intersectoral coevolution, which relies on mutual adaptation across sectors, relies on interfaces and connectivity, which can transform various stages of the VC.

2.3. Rural electrification and complementary investments

In the energy and development field, rural electrification is often seen as a catalyst for economic transformation, supporting industrialisation and market growth. Studies from Africa, Asia, and South America show that electricity, water, and milk flows help modernise and formalise the dairy sector through rural enterprises and cooperatives, reducing barriers to entrepreneurship and export growth (Husnain et al., 2022; Nogueira et al., 2012; Nyokabi et al., 2023; Sarkar et al., 2024). However, electrification alone is insufficient, especially for milk cooling and processing. Complementary investments, cross-sector coordination, and institutional support are essential (Habiyaremye et al., 2021; Nyokabi et al., 2023).

A related research stream focuses on productive energy use, examining how electricity demand grows when paired with support for entrepreneurship and local industries (Aarakit et al., 2024; Hartvigsson et al., 2021). However, this often oversimplifies VCs and treats entrepreneurs as a single group (Aarakit et al., 2024; Vernet et al., 2019). Critics argue for more attention to how specific VCs co-evolve with electricity access and service reliability (Ankel-Peters et al., 2025; Cook, 2013).

In agricultural economies, electricity access can significantly enhance VC activities such as cold storage, processing, and packaging. Innovations such as blockchain and mobile platforms have linked producers to urban and global markets (Rob & Cattaneo, 2021). Studies from Tanzania and the International Renewable Energy Agency (IRENA) highlight that improved agrifood VCs can increase electricity demand, helping utilities finance infrastructure expansion (IRENA, 2021; Osunmuyiwa & Ahlborg, 2022). Conversely, poor electricity quality can discourage participation in VCs (Dijk & Clancy, 2010).

Research on the dairy sector shows that electricity access reshapes DVC structures, affecting institutions, technologies, and rural–urban flows driven by food quality and urban demand (Kariuki, 2016; Van Campenhout et al., 2019). In Uganda and Kenya, policy reforms and investments have enabled community- and private-led cooling and storage, fostering export-oriented dairy industries (Van Campenhout et al., 2019). These countries now host diverse dairy sectors where formal and informal actors coexist and compete (Matangaidze et al., 2023; Van Campenhout et al., 2021). Electrification thus introduces new actors, technologies, and institutions, transforming the DVC landscape.

2.4. Conceptual Framework

2.4.1. Key Concepts

The conceptual framework builds on spatial concepts and socio-technical systems theory, viewing sectoral structures as comprising actors (e.g., farmers, milk agents, processors, retailers, wholesalers), institutions (formal regulations, policies, contracts, standards, and informal norms), technologies, and natural elements (e.g., pastures, cows, bacteria). These *components* are linked through *flows* of information, money, electricity, milk, and materials. While some elements are fixed in space (e.g., electric grids, head offices), many flows, such as electricity, data, and people, move between locations. Electricity and milk flows represent each sector's core function: delivering high-quality services or products to the market. In this study's empirical context, dominant practices are not well institutionalised. There is no clear "regime," but rather a traditional, informal milk VC and a rural energy mix dominated by bioenergy and diesel generators. Both sectors are expanding with new components.

We use the concept of *interfaces* to describe structural overlaps between sectors and apply the economic geography concepts of *absolute and relational proximity* to explain changes in physical location (e.g., transformer near MCCs) and the intensity of interactions (e.g., knowledge, finance, technology) beyond physical distance. We assess the bidirectional impacts between sectors and how they influence each sector's performance. For electricity, this means reliable, affordable services that support sustainable milk production and diverse, high-quality dairy products. Although broader political, environmental, social, and institutional contexts are not part of the sectors themselves, they are critical external influences. Our framework includes these external factors and their role in shaping electricity-DVC interactions, consistent with prior research (Hansen & Coenen, 2015).

Fig. 1 presents a conceptual framework illustrating the interactions between electricity and DVC components, including sectoral boundaries and interfaces. The main arrow represents the flow of technologies, information, knowledge, and finance that enable the flow of electricity and milk. The framework shows that sectors evolve through internal dynamics and interactions with other sectors. As components become more interconnected, both absolute and relative proximities increase within and across sectors.

3. Methodology

3.1. Scope

This study examines the period from 2005 to 2023 across four districts in Rwanda (see the map in Fig. 2). While national and international linkages are acknowledged, the focus is on comparing these districts. The scope is limited to electricity supply and its role in the DVC, particularly in milk cooling and processing. Although broader contextual data were collected, the analysis centres on the electricity and milk processing nexus. The DVC analysis covers supply-side activities such as milk collection, processing, and distribution, excluding market dynamics, consumer demand, on-farm consumption, waste management, and environmental aspects.

3.2. Location of the study area

This study was conducted in the northwestern Rwandan districts of

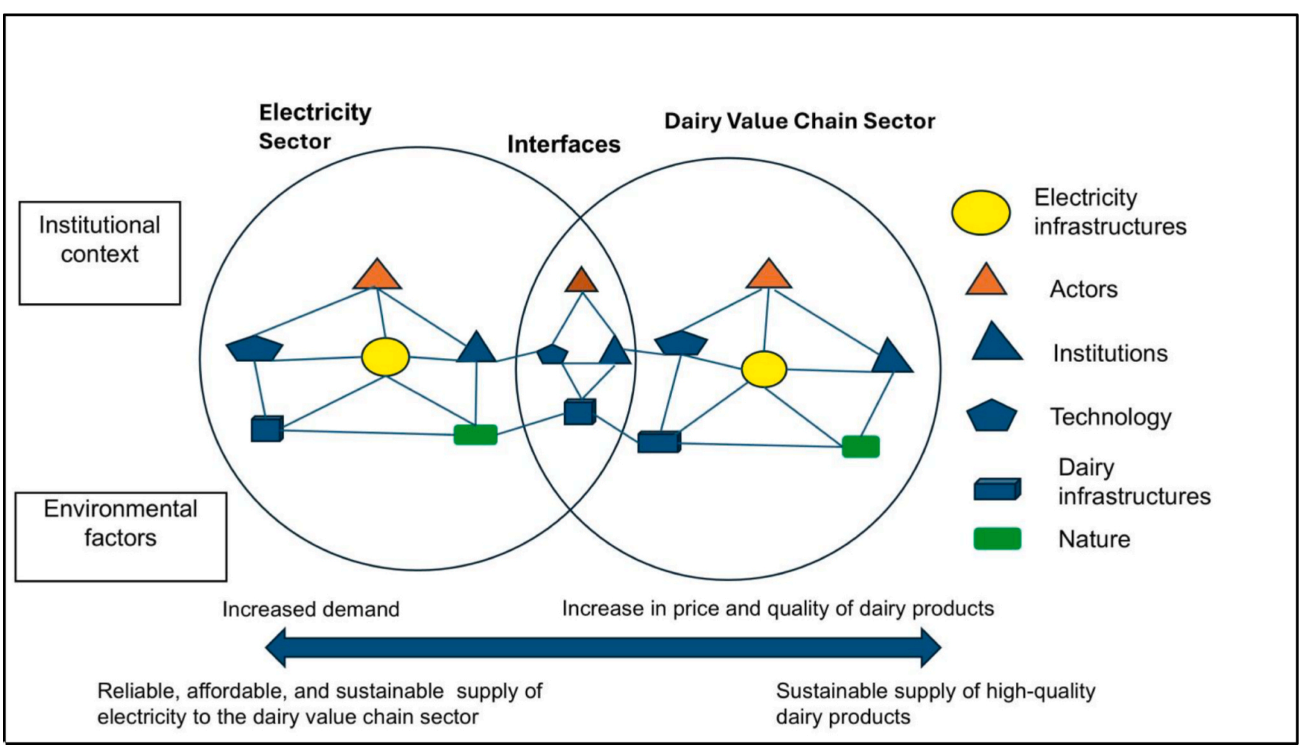
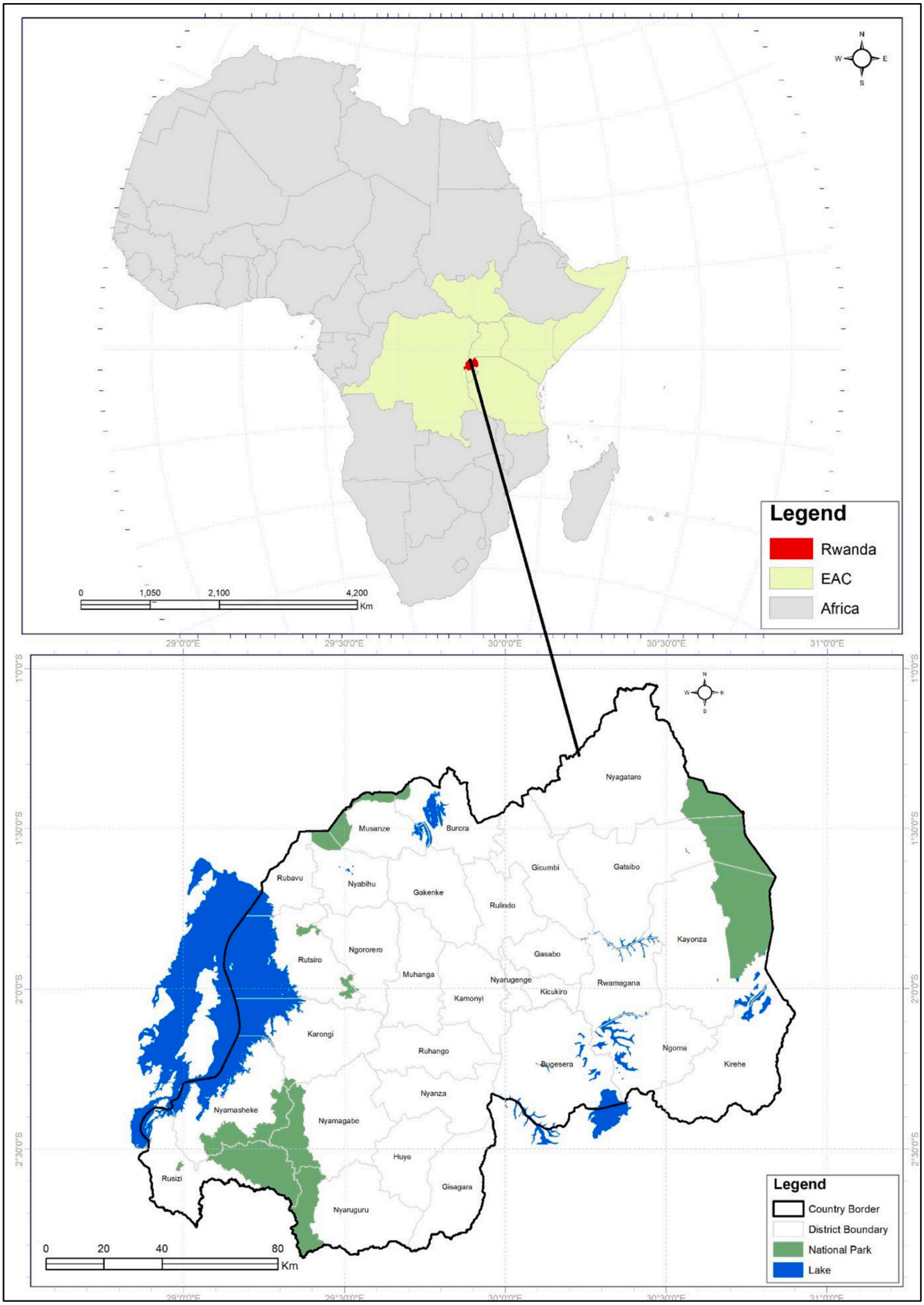


Fig. 1.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Nyagatare
Musanze
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Rwamagana
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Ngoma
Bugesera
Kirehe
Nyanza
Nyamasheke
Nyamagabe
Huye
Rusizi
Gisagara
Nyaruguru
0
20
40
80
Km
Legend
Country Border
District Boundary
National Park
Lake

Fig. 2.

Burera, Musanze, Nyabihu, and Rubavu (see Fig. 3). Rubavu and Nyabihu border the Democratic Republic of Congo (DRC), with Rubavu City adjacent to Goma City, forming a hub for cross-border trade, including daily dairy exports to Goma. Nyabihu and Rubavu districts also encompass a significant portion of the Gishwati Forest's open grazing zone (Tuyisingize et al., 2022). These districts were selected for their geographic advantages, including their location in milk production zones, their cool weather, which is suitable for animal husbandry, their geographic proximity to the Congolese city of Goma, and their significant contribution to the country's milk production.

3.3. Data collection

The study employs qualitative and spatial analyses of primary and secondary data to assess the coevolution of electricity and DVC performance and its role in Rwanda's rural-urban transformation. Data collection was conducted over five months (August to December 2022) and included in-depth and informal interviews, focus group discussions (FGDs), and field observations.

FGDs were conducted on the first day of arrival at each study site, including MCCs and SME processing plants. In this study, all SME processing plants except one sourced milk directly from farmers and agents rather than through MCCs. These discussions provided an overview of stakeholder groups (e.g., farmers and agents), their perspectives, and local milk supply dynamics, which informed the refinement of interview questions for the subsequent interviews conducted over the following days, particularly those with milk suppliers.

The lead researcher and a research assistant conducted field visits to nine MCCs, three Small and Medium Enterprises (SMEs), one large-scale dairy processing plant, and two cooperative kitchens across rural areas in four districts of Rwanda: Musanze, Rubavu, Nyabihu, and Burera. Additionally, three distribution points and four retail outlets (mini-markets) were visited in the cities of Kigali, Musanze, and Rubavu cities to capture perspectives on the relationship between electricity, dairy product distribution, and marketing practices. In total, 143 stakeholder interviews were conducted across these sites (see Appendix 1 for details). Participants were interviewed individually using category-specific semi-structured interview guides. Respondents included milk suppliers, MCC staff and presidents, dairy processors, dairy product retailers, and government officials.

Before each interview, the researcher and research assistant explained the study's ethical procedures, including measures to protect participant privacy, ensure data confidentiality, maintain secure data storage, and use collected information solely for academic purposes. Despite these assurances, some participants expressed concerns that audio recordings might be used for radio broadcasting or surveillance purposes. Consequently, no audio recordings were made. Participants' responses were recorded in writing during the interviews, and the notes were subsequently reviewed and verified in the designated sections of the interview guides. This was done to build trust, encourage voluntary participation, reduce dropout and promote open and honest responses during the interviews.

To examine the coevolution of electricity access and dairy value chain (DVC) performance, spatial datasets comprising administrative boundaries, elevation, electricity networks, road infrastructure, land use, lakes, and wetlands were integrated with interview and observational data. This mixed-methods approach enabled the analysis of both spatial and socio-technical factors shaping dairy value chain development and electricity access.

Preliminary findings were discussed during a research and policy dialogue held in Kigali on April 29, 2025. The purpose of the dialogue was to validate the interpretation of the findings, correct any misunderstandings, gain deeper explanations, and facilitate knowledge sharing among participants. The dialogue brought together participants from diverse backgrounds, including representatives from government ministries and agencies; district animal resources and cooperative officers from Musanze, Rubavu, Nyabihu, Burera, and Gicumbi; SMEs and processors; MCC cooperative presidents; international organizations such as United Nation Children Fund (UNICEF); donors such as the Swedish Embassy; and academic institutions, including Chalmers University of Technology and the University of Rwanda's Colleges of Science and Technology and of Agriculture and Veterinary Medicine.

3.4. Data analysis

NVIVO software was used for content analysis, guided by a codebook that evolved to include emerging themes such as actor networks and DVC performance. ArcGIS 10.8 was used to map visualisations, track geographic expansion and changes in proximity within the DVC. Limitations include sampling bias from snowball sampling, the absence of some government organisations due to non-response, and the absence of Non-Governmental Organisations (NGOs) perspectives due to office closures. We did not interview the Rwanda Energy Group (REG), but this organisation was often mentioned by local-level actors, and we thus have not been able to validate all stated interactions with REG officials. Inputs from secondary sources such as project and policy reports and newspaper articles mitigated this constraint. Time constraints also prevented household and farm visits. However, extended stays at MCCs allowed for diverse participant selection based on milk supply volumes. Triangulation through multiple methods and local assistant insights enhanced data validity and helped identify insincere responses, enriching understanding of DVC dynamics.

3.5. Geographical context for the coevolution of the DVC and electricity sectors

This section introduces the geographical and societal context of the case study and sets the scene for understanding the coevolution of electricity and the DVC through historical trajectories. Rwanda, a rapidly developing sub-Saharan African country, has recorded an average annual Growth Domestic Product (GDP) growth rate of 8.9% for 2024 (WB, 2025) (see Table 1 for country-level statistics).

Since independence, Rwanda's electricity sector has undergone significant transformation. Development in the early post-colonial period was constrained by limited resources and low investment, resulting in persistent deficits in generation and transmission. Until the early 2000s, domestic generation capacity remained at 41.25 Megawatts (MW) from hydropower plants. To supplement domestic supply, Rwanda relied on electricity imports from DRC and Uganda (Safari, 2010).

During the 2000s, heavy reliance on hydropower increased vulnerability to climate variability. Severe droughts triggered electricity shortages. In response, Rwanda procured added capacity from privately owned diesel power plants, which imposed high costs, straining the government budget (Bimenyimana et al., 2018; Safari, 2010).

Between 2010 and 2022, electricity generation expanded rapidly (see Table 2), driven by resource diversification and institutional reform (Brunet et al., 2021). In addition to hydropower, the government developed peat, solar, and methane gas resources. Total domestic generation reached 276 MW (REG, 2025). Regional cooperation around hydropower further strengthened supply. Electricity infrastructure expanded alongside generation capacity. High-voltage transmission lines were upgraded. Despite these gains, system reliability remains a challenge (REG, 2024; REG, 2023).

The sector has also been restructured institutionally, with the unbundling of the state-owned utility and the establishment of the Rwanda Energy Group (REG), comprising Energy Development Corporation Limited (EDCL), responsible for generation and transmission planning, and Energy Utility Corporation Limited (EUCL), responsible for distribution and market operations. Policy reforms enabled private-sector participation through partnerships between REG and local and foreign firms. These changes facilitated the spatial expansion of electricity access, particularly in rural areas. According to the electricity

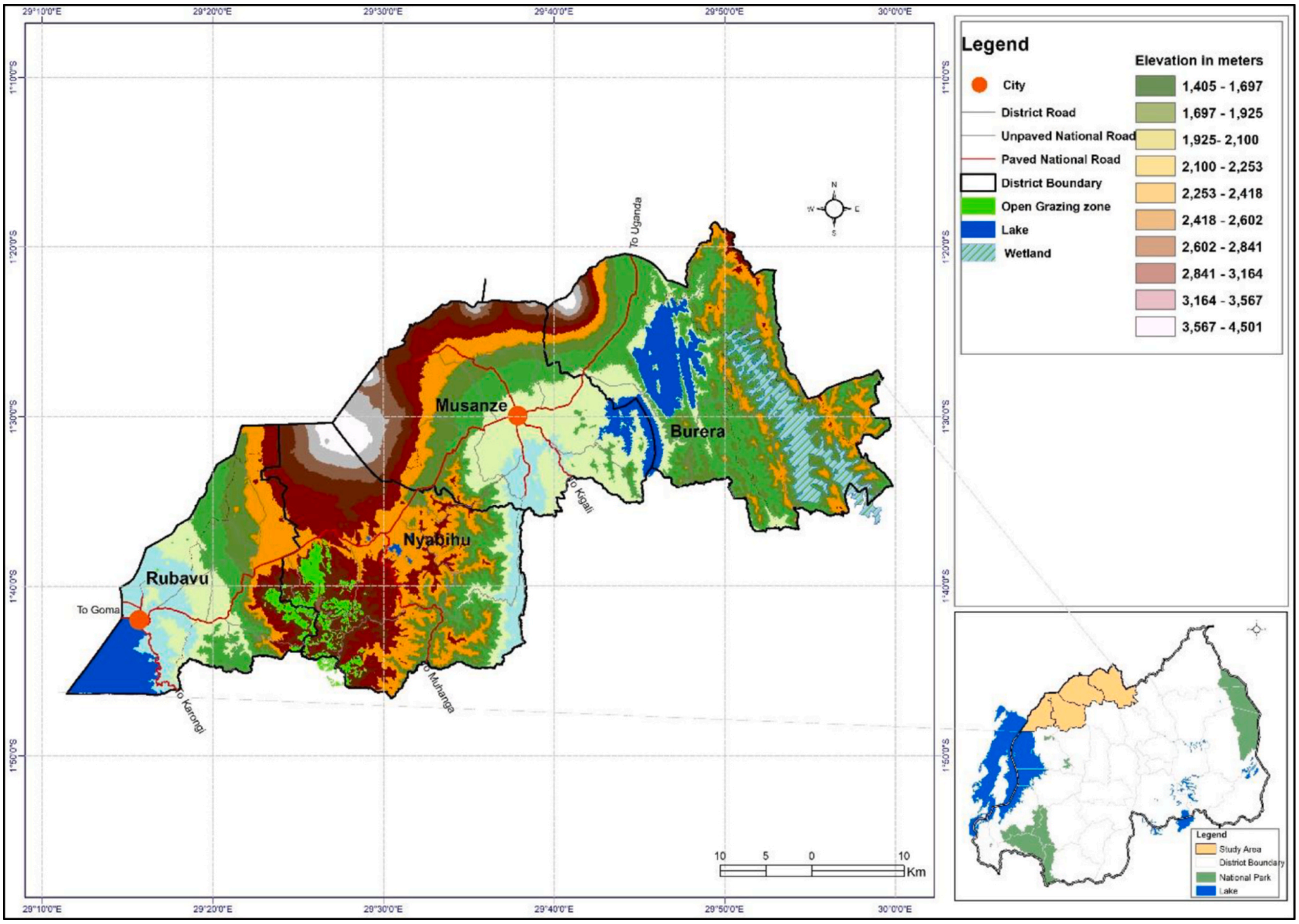

Fig. 3.

Table 1
Rwanda socio-economic Indicators

Indicators	Data
Area (sqkm)	26,338
Population	13.5 million
Population density (Inhabit/sqkm)	501
Annual population growth (%)	2.3
Farm size per household (hectare)	0.4
Poverty rate (%)	30.5%
Gross domestic product (GDP)	14,251 Million USD
Economic activities contributionto the Growth Domestic Product (GDP) (%)	Agriculture 27%Service 44% Industry 22%
Human capital index; medium human development	0.578Rank: 159/193
Key export	Coffee, tea, minerals

Sources: WB, 2025; NISR, 2024

master plan, network expansion is anchored in industrial development in secondary cities and semi-urbanised rural areas, and in promoting productive electricity use (REG, 2024).

The production of milk holds cultural significance and a central role in Rwanda's socio-economic transformation vision. The sector is influenced by multiple contextual factors, environmental, demographic, climatic, technological, and political. Historically, cattle farming and milk production have been central to rural livelihoods, and culturally, cattle ownership symbolizes wealth, social status, and economic stability. Milk is a vital source of protein and essential micronutrients, particularly for vulnerable groups such as children and pregnant women (Habiyaremye et al., 2023; Karenzi et al., 2013; Niyonzima et al., 2025).

Environmental conditions for dairy farming are most favourable in the eastern and northwestern regions, where open grazing areas have expanded near protected zones (Clay, 2019). However, land scarcity poses a major challenge nationwide, with a population density of approximately 503 inhabitants/km^2 (National Institute of Statistics of Rwanda [NISR], 2023). In the large part of the country, rising land pressure limits open grazing and competition for land has pushed farmers toward zero-grazing systems (Ronnie et al., 2022).

National and regional policies have reorganised milk sourcing by dividing production areas into designated milksheds to streamline milk processing and distribution (Habiyaremye et al., 2023; Heifer International, 2023; Karenzi et al., 2013). At the local level, district industrial master plans target the dairy sector (International Fund for Agricultural Development [IFAD], 2016, 2025). Within the agricultural sector, the dairy sub-sector has experienced rapid growth, largely due to government investments to boost milk production and support farmers. Currently, the sector supports over 100,000 households and employs a significant share of Rwanda's agricultural workforce, which accounts for about 70% of the population. Initiatives such as the Girinka[2] Program, which provides cows to vulnerable households, and genetic improvement through crossbreeding have increased average milk yields from 1–2 litres to 5–7 litres per cow. Consequently, national milk production increased by 193% (Niyonzima et al., 2025). This growth reflects a transition from subsistence to a more formalised dairy economy, supported by the expansion of MCCs as hubs for aggregation and industrial processing, export and dairy products import substitution (Heifer International, 2023). The sector now contributes approximately 6% to

[2] "Girinka", translated from Kinyarwanda, means "own a cow".

Table 2
Rwanda's energy system

S/N	Category	Details	Quantities
1	Transmission Network upgrading	Voltages upgrades (kV) 2013-2024	70 to 110
		New constructions (kV) 2015-2024	110 to 22
		Total transmission length in (kms) in 2024	1158
		Total transmission length in (kms) in 2022	973
	Transmission network breakdown	110 kV (%)	66.6
		220 kV (%)	33.4
2	Distribution network	Medium voltage (km)	10,520
		Low voltage lines (km)	18,456
3	Electricity access	Total access %	84.5
		Access from the national grid (%)	59.6
		Off grid solar (%)	25.0
		Mini grid standalone (%)	16.0
		Grid connection (number)	1,464,166
		Off-grid connection (number)	618,222
4	Generation infrastructure ownership structure	Government (%)	64
		Independent Power Producers (IPPs) (%)	26.5
		Import and shared (%)	9.4
		Power annual outage duration (minutes) (2022-2023)	1,463
		Annual power outage duration (minutes) (2023-2024)	1,221
	Main causes of power outages (%)	Earth fault (2022-2023)	39.4
		Over current fault (2022-2023)	33.2
		Under frequency event (2022-2023)	19.7
		Emergency loadshedding (2022-2023)	2.3
		Planned works (2022-2023)	1.8
		Emergent work (2022-2023)	3.5

Source: REG, 2024; REG, 2023

Rwanda's GDP (Tramsen & Mugo, 2024). The Government of Rwanda (GoR) has provided MCCs with electricity, first via off-grid generators and later via grid extensions and solar panels (Ndahetuye et al., 2020). These interventions, which initially focused on Gishwati and Umutara, later expanded nationwide (TechnoServe Rwanda, 2008).

Rwanda's domestic dairy sector continues to attract limited FDI[3]. The processing landscape is largely dominated by one local company (see Table 3 for details), which either established directly or acquired processing plants from the government in each of the country's primary milk–sheds(Nyenga, 2016; Sabiiti, 2025; Times reporter, 2012) (Table 3). MCCs that supply these processing plants were established through government investments and have been ceded to farmers' cooperatives for day-to-day management, operation, and maintenance of the infrastructure (Habiyaremye et al., 2021, 2023). Under this arrangement, MCCs are responsible for operating the facilities, while the government retains oversight and provides support for technologies, capacity building, and milk quality initiatives (TechnoServe Rwanda, 2008).

4. Results

This section presents the results on the coevolution of electricity and dairy sectors in Northwestern Rwanda's Western Milkshed. It focuses on cooperative-based MCCs, infrastructure integration, and sectoral challenges. Key actors, including DVC actors and the electricity utility, are examined within their geographic and institutional contexts.

4.1. Evolution of the structures of the dairy sector

The modern dairy sector in the region emerged in 1988 with the establishment of the country's first processing facility in Gishwati, under the Gishwati-Butare-Kigali (GBK) project, funded by the World Bank (Bizimana & Hategekimana, 2024). This facility produced pasteurised milk, yoghurt, cheese, and butter for urban markets in Rubavu, Musanze, and Kigali. A second facility followed in 1989 in Nyabihu District. Before 1994, dairy consumption was limited to expatriates and urban elites, and Rwanda continued to import dairy products despite local production (Rwanyagahutu, 1988).

The 1994 genocide against the Tutsi devastated the sector, leading to the looting and closure of facilities. Without rehabilitation, farmers reverted to traditional preservation methods. Poor infrastructure and reliance on mini trucks led to high spoilage rates and financial losses. Recovery began in 2006 with the rise of SMEs and the establishment of MCCs, which improved milk quality, storage, and distribution. The first MCC in Rubavu, supported by the PADEBL (Projet d'Appui au Développement d'Elevage Laitier: Dairy Cattle Development Project), introduced milk-cooling technologies and cooperative models (Karenzi et al., 2013). Electrification further enhanced storage, enabling supply to processors such as Inyange Industries Ltd and Rubirizi Dairies. However, the concentration of processors in Kigali created market access challenges for rural farmers.

To address supply chain inefficiencies, the Ministry of Agriculture and Animal Resources (MINAGRI) promoted direct sales to traditional cooperatives, also known as "kitchens," that specialised in fermented milk exports to Goma City (DRC). Despite proximity advantages, farmers faced irregular payments and logistical hurdles. The government responded by encouraging formal contracts among MCCs, intermediaries, and processors. MCCs in Rubavu and Nyabihu diversified their partnerships accordingly. In 2012, MINAGRI initiated the Mukamira Dairy plant, completed in 2017 with 75% government and 25% cooperative ownership. In 2018, the government sold its stake to Mukamira Dairy Ltd, a subsidiary of Inyange Dairies Ltd. This integration of MCCs into formal VCs marked a significant step in sectoral transformation[4].

The operation and privatisation of the large-scale processing plant came with new practices and standards that showcased the upgrading process. These include the testing of antibiotic contents and microbial growth, the latter being dependent on the milk cooling efficiency and contracting with MCCs. The continuation of the contract is based on the MCC's compliance with the processor's quality standards. This evolution has contributed to the diversification of dairy products and the geographical expansion of the DVC.

Geographically, the dairy processing units have expanded from the core zone of Nyabihu to Burera District; and the MCCs have expanded their sales from the local market to the market in Kigali and other districts. Four processors were operational at the time of study. In addition to the geographical expansion of the supply chain and market, the DVC has expanded from locally made products to modernised products. For instance, the leading large-scale processor has broadened its product portfolio and has expanded into international markets, including the DRC, Burundi, and Kenya, establishing sales contracts with private distributors. Currently, in addition to the traditional sub-VC, the structure (see Fig. 4) of the DVC testifies to the coexistence of three modern standardised sub-VCs, which are highly dependent on the supply of reliable, affordable and sustainable electricity:

Sub-VC 1 is the traditional fermented milk sub-VC, which centres on kitchens in the Rubavu and Nyabihu districts. The kitchens are managed by women's associations (Zirakamwa and Amata Meza Kanzenze).

[3] During the study we found that only one SME processing plant was bought and operated by Zimbabwean company, Afrisol Ltd.

[4] Following the sale of the factory to Inyange Industries, the farmers' ownership share decreased to 2%, and Inyange Industries acquired 88% of the shares.

Table 3
Large-scale dairy processing plants' ownership

Processing factory	Milkshed	District of location	Ownership	Origin of the owner	Products
Inyange Industries	Central (Kigali)	Masaka, (Kicukiro),	Crystal Ventures Ltd / Inyange Industries (100%)	National	UHT, pasteurised milk, fermented milk, yoghurt, cheese, cream ghee, butter, juice and mineral water
Mukamira dairy Ltd	Half Western and half Northern (Gishwati)	Mukamira (Nyabihu)	Crystal Ventures Ltd/ Inyange Industries (98%) and Farmer cooperative (2%)	National	UHT, pasteurised milk, fermented milk, yoghurt, gouda cheese, butter
Savannah Dairy	Eastern	Nyagatare	Crystal Ventures Ltd/ Inyange industries	National	Powder milk
Giheke Dairy	Western	Giheke (Rusizi)	Crystal Ventures Ltd /Inyange Industries (98%)Farmer cooperative (2%)	National	Fermented milk, cheese, yoghurt , butter, gouda and mozzarella cheese
Nyanza Dairy	Southern	Nyanza	Agro-Processing Trust Corporation (APTC) Ltd	National	Fermented milk, gouda and mozzarella cheese, butter, yoghurt
Blessed Dairy	Northern	Gicumbi	Ngirente Milton	National	Yoghurt, fermented milk, butter, cream and mozzarella cheese
Burera Dairy[a]	Northern	Burera	African Solution Private Ltd	Zimbabwe	Fermented milk, Gouda and mozzarella cheese, butter,

Source: Garcia et al., 2023; Habiyaremye et al., 2021 and interviews
[a] The processing plant was classified as a SME but results show that it is majority owned by transnational company that purchased it from the government.

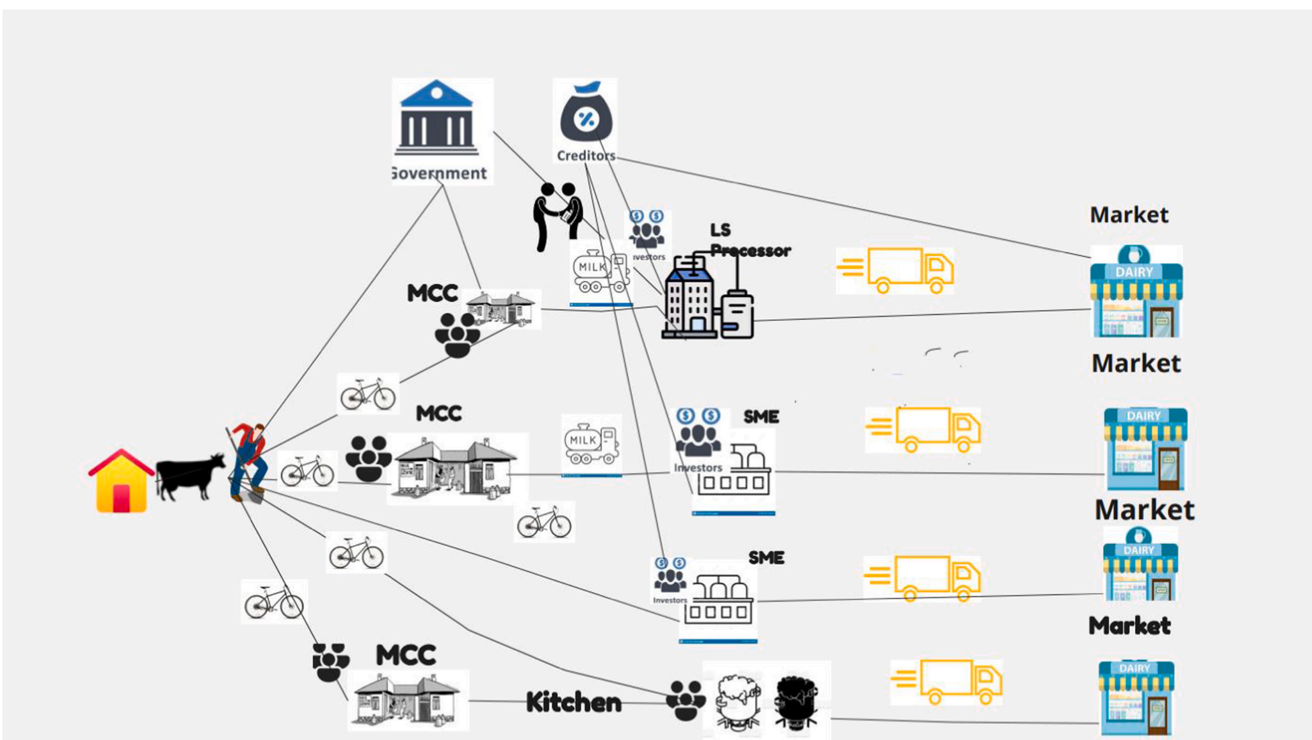

Fig. 4.

These kitchens collect milk from farms or receive it from cattle keepers, MCCs, and vendors. They process fermented milk using traditional pasteurisation methods involving firewood and overnight fermentation. The milk is packed into trucks and shipped to Goma City for sale. Considered as informal, this sub-VC is different from the illegal market because it follows some testing standards and sometimes sources the milk from the MCCs. In contrast, the illegal channel does not follow any testing standards.

Sub-VC 2 is built around SMEs in Nyabihu and Rubavu Districts. The SMEs produce cheese, yoghurt, butter, and fermented milk. Unlike the traditional sub-VC, these SMEs do not work with MCCs but compete with them for milk sourcing. They rely on a network of agents who provide cash and loans to procure milk from farmers. Individual farmers also supply milk to this sub-VC. These SMEs primarily serve markets in Kigali, Musanze, and Rubavu; some have extended their market to Nairobi (Kenya) and Goma (DRC).

Sub-VC 3 is centred on two MCCs that discontinued their contract with a large-scale processor due to disagreements over milk quality and quantity issues. Instead, they partnered with an SME processing plant initially operated by the government but later privatised and sold to company co-managed by Zimbabweans and Rwandans (BP1). The processor produces various dairy products and buys grade 1 and grade 2 milk[5], focusing less on bacteria growth and antibiotics than the

[5] Grade 1 milk fulfils the requirement of quality standards, including the fluidity standard, such as the lack of water content or souring, microbiological counts, and the lack of pesticides, antibiotics and aflatoxin. In Rwanda, it is used in the production of UHT and industrial pasteurised milk.Grade 2 milk does not necessarily meet the fluidity quality standard (it may be coagulating or souring); it is issued for cheese, butter processing and the fermented milk.

processors in sub-VC 4. The market for BP1 is primarily in the cities of Kigali and Musanze and commercial centres in the Burera District. An attempt to expand the market to Rusizi City was unsuccessful.

Sub-VC 4 revolves around the large-scale processor Mukamira Dairy, a subsidiary of Inyange Dairies, a private dairy and beverage conglomerate operating in diverse sectors, including dairy, mineral water, and juice. This processor relies on a network of MCCs in the Nyabihu, Musanze, Rubavu, and Rutsiro Districts. Due to stringent compliance with milk quality standards and competition from other buyers, the number of MCCs supplying milk fluctuates occasionally. The large-scale processor has established a sales network in ten cities in Rwanda, with a significant presence in Kigali, where six distributors are located. Facing cost-recovery challenges and dependence on government programs for rural consumption of Ultra High Temperature (UHT) milk, the processor has relocated its UHT and pasteurised milk operations to Kigali City, where 70% of its milk is consumed. Only cheese, yoghurt, fermented milk, and butter remain at the Mukamira site. A company representative explains:

"*Our company has operated for four years without recovering its investment. In rural areas, UHT milk is mostly accessed through government programs. Without state support, processed milk is mainly consumed by the urban elite." (Interview with Processing Manager 2, 2022)*.

This strategic decision reduced transport costs and placed production closer to Kigali's commercially viable market, giving the large-scale processor a competitive advantage in supplying the most in-demand products.

While distributors sourcing from the large-scale processor still incur transport costs, some SMEs deliver directly to urban clients like supermarkets and mini markets. These strategies help SMEs maintain strong customer relationships. This contrast highlights the differentiated approaches to urban market proximity among dairy processors, shaped by their scale and resources.

4.2. Geographical evolution of the electricity sector in the region

The geographical evolution of the electricity sector in the study area is marked by the expansion of the network and improved flow stability and reliability. The sector's evolution started in 1984 with the connection of the Mukungwa and Ntaruka hydropower plants (built in 1957), linking Gisenyi Town (now Rubavu City) to the national grid via the Musanze sub-station (Camp Belge). This aimed to electrify the emerging tea industry in Nyabihu, Rubaya (Nyabihu District), and Pfunda (Rubavu District), and connect commercial centres along the Musanze-Rubavu corridor. This period focused on distributing electricity to villages and commercial centres along the main road and connecting the GBK[6] project in Gishwati natural reserves, until the 1994 genocide devastated infrastructures, including power systems.

Efforts to rebuild and expand the grid resumed in 2013, with government and international investments aimed at expanding the network, enhancing reliability, and integrating renewable energy, particularly in medium-voltage lines in rural areas (see Table 4). The Nyabihu substation and a new transmission line reinforced the network. The Giciye I, II, and III micro-hydropower plants were integrated into the grid to support Northwestern Rwanda's industrialisation and minimise the unreliability. According to MININFRA and REG[7], these improvements were expected to meet the economic development demands, including the establishment of new industries and large power consumers. Integrating renewable energy reduced reliance on non-renewable sources, such as the diesel generators at Mukungwa Hydropower station, which were phased out in 2023. Further investments in a high-voltage line in 2022 reinforced the region's network. This high-voltage line was extended from Mukungwa hydroelectric station to Mukamira substation.

4.3. The geographical dimensions of interfaces between electricity and the DVC

For the DVC, electrification in the districts began in 2004, with the first processor connected to the existing grid, and the first MCC connected in 2006, when it began operations. The grid interface for the dairy sector was both specific to MCC sites and temporally dependent on project timelines and funding. The majority of MCCs in the study area were initially relying on diesel generators, especially in Nyabihu because they were located in open farming zones far away from the grid. In 2016, the construction of medium voltage lines enabled the connection of multiple MCCs, using either shared or private transformers. MCCs in Musanze and Burera districts are connected to shared transformers from the old electricity network on the transmission line built in 1984. In contrast, in Nyabihu, most MCCs have private transformers (except NP2 and NM1), which enhance the reliability of electricity supply in these locations (see Table 5 for details). As the subsequent sections will demonstrate, this spatial expansion of electricity infrastructure plays an essential role in the DVC development.

Electrification has fostered new interfaces and interactions among key actors, including MCCs, processors, REG, MINAGRI, and Rwanda Utilities Regulation Authority (RURA). In Nyabihu and Rubavu, medium-voltage lines were extended to MCCs and processing units through coordination by REG and MINAGRI under the Rwanda Dairy Development Project (RDDP), which funded the infrastructure. REG, as the sole contractor, handled planning, mapping, cost estimation, and installation, and later assumed responsibility for supply, maintenance, and advisory services. Initially, off-grid fuel generators provided by PADEBL and the Rwanda Agriculture and Animal Resource Development-Post Harvest and Agribusiness Support Project (RAB-PASP) enabled milk cooling, but these were costly and dependent on the fuel supply chain. Grid electrification significantly improved milk quality and market access by ensuring more stable cooling. While reducing reliance on fuel, MCCs and processors still use generators as backup during outages.

The integration of electrification with cooperative models at MCCs further enhanced electricity access and affordability by enabling farmers to share resources such as generators and grid connections. Subsidies lowered electricity access costs to MCCs, making it accessible to farmers unable to invest in individual cooling infrastructure. Additionally, solar water heaters reduced reliance on the grid, wood fuel, and Liquefied Petroleum Gas (LPG) for heating water, reinforcing the adoption of clean energy in DVC operations and contributing to environmental sustainability.

With the new power stations located in Burera, Musanze, and Rubavu districts, the grid-DVC interface spread across the four districts. Cables were drawn inside the MCCs and processing units to allow the flow of electricity, and transformers were installed nearby to stabilise this flow. Results demonstrate that three-phase connections and meters are most suitable for running the cooling and processing activities in the DVC. The lack of pre-installed three-phase circuits, meters, and related transformers has made it difficult to maintain a stable electricity supply at their facilities, as demonstrated by one MCC in Musanze and one SME processor in Rubavu districts. With the polyphase system comes the demand for and responsiveness from REG to provide repairs. For instance, according to MCC actors in Nyabihu District, REG can change or repair the transformer and related networks at any time they break, demonstrating that technical assistance from the electricity utility to MCCs has improved reliability and contributed to the replacement of fuel generators.

In addition, at the local level, REG influences MCCs' and the

[6] GBK, by the acronym, Gisenyi, Butare, Kigali, was a World Bank-funded Integrated Forestry and Livestock Project that was aimed at planting intensive forestry species for commercial purposes and replacing indigenous cattle with modern dairy ones. It integrated both afforestation and creation of modern farms in the Gishwati Forest.

[7] REG stands for Rwanda Energy Group. It is the national electricity utility

Table 4
Evolution of the electricity network in the study area

Expansion project	Districts or villages connected	Source power station connected	Location of the sub-station connected	Capacity	Year
Interconnection from Burera, Musanze, Nyabihu to Rubavu districts	Connection of Musanze, NyabihuRubavu District	Ntaruka,MukungwaGihira	Mukungwa, NtarukaCamp BelgeRubavu	70kV (kilovolts)	1984
Upgrading of the Interconnection of Mukungwa, Ntaruka, and Gihira Power Plants	Northwest:Connection of Musanze, Nyabihu and Rubavu District	Mukungwa, NtarukaGihiraGiciye I,Giciye IIGiciye III	Mukungwa, Ntaruka, CampBelgeRubavu	110 kV	2013
Construction of 2 medium voltage lines to the MCCs in Gishwati farming zone in Nyabihu and Rubavu districts	Connecting Arusha Nyiragikokora villages in Nyabihu District and and Nkomane in Rubavu District	The upgraded 110 kV from Camp Belge	Camp Belge	30 kV for each line	2016
Construction the high voltage lines to reinforce the network in the northwestern region	Northwest:Musanze, Nyabihu Rubavu Districts	Mukungwa, NtarukaGihiraGiciye IGiciye IIGiciye II	Mukungwa, Ntaruka, CampBelge,Nyabihu (Mukamira)Rubavu	110kV	2022

Sources: REG, 2022, 2023 and interviews

Table 5
Geographical location of the DVC infrastructures and history of access to the electricity grid

Name of infrastructure	Type	District	Sector	Year of operation	Year of connection to the grid	Use of the backup generator
NP1	Large scale processor	Nyabihu	Mukamira	2017	2017	Yes
NP2	SME processor	Nyabihu	Bigogwe	2011	2011	No
RP1	SME processor	Rubavu	Kanzenze	2004	2004	Damaged
BP1	SME processor	Burera	Cyanika	2016	2016	Yes
MM1	MCC	Musanze	Kinigi	2007	2007	Damaged
MM2	MCC	Musanze	Shingiro	2014	2014	Yes
NM1	MCC	Nyabihu	Bigogwe	2008	2008	Yes
NM2	MCC	Nyabihu	Rambura	2008	2016	Yes
NM3	MCC	Nyabihu	Bigogwe	2008	2016	Damaged
RM3	MCC	Rubavu	Kanama	2008	2016	Damaged
RM1	MCC	Rubavu	Kanzenze	2006	2006	Damaged
RM3	MCC	Rubavu	Kanama	2018	2018	No
BM2	MCC	Burera	Cyanika	2010	2010	Yes

Sources: interviews

processors' maintenance practices. For instance, MCCs that report a good relationship with REG experience fewer disruptions and receive better support in maintaining their operations. This cooperation helps minimise operational disruptions and ensures a reliable electricity supply, as testified by some MCC presidents:

"REG helped us fix fallen poles. Once, we had an issue with electricity not flowing to the machine, so we called REG. Their assistance prevented us from experiencing a loss because we could continue working without using the generator." (Interviews with MCCs presidents 7 and 8, 2022).

This positive collaboration ensures prompt repairs and a reliable power supply, enabling the smooth functioning of these centres. On the other hand, MCCs with less effective collaboration with REG experience more frequent power outages and longer repair times, which impacts their overall efficiency because the milk they collect is damaged, poured, and sometimes sold to illegal traders at lower prices (see Table 6 for details).

Reliable and affordable grid electricity has enabled the use of communication tools and the integration of banking and telecommunication services into the DVC. MCCs send milk invoices to processors via email, and processors and banks transfer payments online. Electricity meters are calibrated for different pricing categories; REG requires MCCs and processors to use three-phase meters because three-phase power supply better withstands voltage fluctuations, thereby reducing the risk of forced equipment shutdowns. Pricing and user categorisation involve consultation among REG, RURA, and the Ministry of Infrastructure, with both SMEs and large-scale processors classified as industrial users, reportedly resulting in lower electricity costs than other user categories.

Table 6
Electricity issues at different DVC locations

Location	Issues	Mitigation
NM3	Severe outages lasting up to a day	Leading to milk spoilage and equipment damage, with non-functional backup systems exacerbating the issue
RM1	Stable power supply	Rare outages quickly addressed by REG
RM2	Two outages per month	Functional generator to maintain operationsSometimes, pump damage incurs additional manual labour costs (4,000 RWF(2.72 USD)
RM3	Significant challenges with frequent daily power cuts lasting 2-3 hours, leading to milk spoilageThe downgraded milk sold at a loss (approximately 50 RWF per litre)	No back-up generator is used to mitigate the issuesMCC disconnected its cooling machines and opt to collect, test and sell the milk to the informal market
BM1	Relies on a generator to mitigate occasional power cuts, which adds to operational costs	Back-up generator is used during power cuts
NM2	Short and manageable outages	Backup generatorOccasional electricity fluctuations can affect milk quality

Sources: Interviews

However, there are complaints that electricity costs remain high for DVC actors. A review of a sample of electricity invoices from one processor indicates that this processor has accumulated payment arrears[8].

[8] Unlike MCCs, processors classified as industrial users use postpaid meters, with REG issuing electricity invoices to them via email.

Prepaid meters help manage electricity use by allowing users to purchase credit in kilowatt-hours. DVC actors, including MCCs, use technological interfaces such as mobile money platforms and banking applications to buy electricity, receiving token codes to restore power supply. Usage data influences decisions about the timing of electricity consumption, particularly for cooling. For example, an MCC in Musanze District adjusts electricity purchases based on cooling needs and price levels, buying only enough electricity per cooling cycle to match milk collection volumes and processors' milk demand.

Electricity prices act as a negotiation interface between actors in the DVC and the energy utility. For example, MCC managers expect that their high electricity costs could prompt negotiations between MINAGRI through the RDDP and REG to advocate for lower tariffs. However, REG retains greater authority over tariff proposals, as it prepares them for review. REG does not respond directly to MINAGRI's informal requests on behalf of MCCs, possibly because these requests were not formally documented. In practice, decisions on electricity tariffs are made by RURA in consultation with the Ministry of Infrastructure, which oversees the electricity portfolio and submits the tariff proposal to the Cabinet for approval. After Cabinet approval, RURA publishes the tariffs.

Compared with other districts, Nyabihu and Rubavu exhibit more substantial structural development of the DVC, with more MCCs, processing units, and interfaces between the dairy and electricity sectors. Nyabihu, home to the large-scale processor, has more intensive interactions with REG, including financial and information exchanges via telecommunication tools, as well as discussions on pricing, maintenance, and reliability. Two MCCs were connected to the grid in 2016, increasing engagement with MINAGRI and REG. In contrast, Burera's single processor and MCC show limited interaction with REG. Musanze's MCC (NM2) also reports weak engagement and has not adopted internet-based interfaces with the electricity sector.

4.4. Key challenges in the co-evolution of the electricity and the DVC sectors

This section discusses the performance of the electricity and DVC sectors and their related challenges. The three main challenges identified by actors are reliability, affordability, and maintenance practices.

4.4.1. Reliability

The reliability of electricity supply is a critical factor in the coevolution of Rwanda's electricity sector and the DVC. Inconsistent power supply compromises milk quality, disrupts dairy processing operations, and undermines the financial sustainability of MCCs. Since 2013, grid reliability has improved, yet spatial disparities persist, particularly affecting MCCs in Musanze District. Two MCCs in this district exemplify these challenges. Frequent and irregular power cuts, coupled with voltage fluctuations, result in milk spoilage and economic losses. These issues stem from outdated infrastructure, including medium-voltage lines and transformers that have not been upgraded. One MCC, connected via a line built in the 1980s to serve health and commercial centres, did not benefit from infrastructure support under the RAB-PASP or the RDDP. Its transformer is shared with high-demand users, six grain mills, a health centre, local administrative office and the commercial centre, leading to frequent outages, especially during the rainy season[9].

Overvoltage after shutdown damages sensitive equipment, such as milk tank ventilators, with repair costs reaching 200,000 RWF[10](equivalent to 136.08 United States Dollars (USD))[11]. While one MCC has a functional backup generator, the other's generator is inoperative, and its rooftop solar system is non-functional due to maintenance issues. MCCs with reliable backup systems experience fewer disruptions and reduced economic losses. However, power cuts can last up to a full day, and in some districts, response times from the REG are delayed, exacerbating the problem.

Processors face significant challenges due to unreliable electricity, which affects operations and necessitates various adaptation strategies. In Burera District, an SME processing plant frequently experiences power outages and voltage fluctuations, disrupting production and causing economic losses. One processor explained:

"*Power cuts do occur, but REG informs us when they happen. They are infrequent and usually caused by breakdowns. Most last around 20 minutes. However, prolonged outages, especially during cheese production, can disrupt the pressing process, which relies on electricity. We can lose about 5 kg of cheese per trimester." (interview with processing plant manager 14, 2022).*

In contrast, processors in Nyabihu District are affected by outages caused by phase loss during the rainy season:

"*We have never had major issues with power cuts, but once, after pouring milk into the machine, a full-day outage caused a loss of 500 litres, worth 150,000 RWF(≈120 USD). These issues usually occur when it rains. REG responds promptly when contacted, and we maintain a good relationship." (Interview with processing plant manager 4, 2022).*

For a large-scale processor, grid reliability has improved since a new substation was built: *"Power outages were a major issue before the substation. Now, it's rare, though short-duration cuts still occur. We use a backup diesel generator, but fuel costs have decreased thanks to improved reliability"* (Interview with processing manager 1, 2022).

As a result, this processor now plans to establish a chilling plant to supply milk to the new powdered milk factory in Nyagatare District (Eastern Milkshed).

In Rubavu District, another SME processor faces long-standing issues with voltage fluctuations. These have forced a shift to firewood for pasteurisation, limiting the use of modern machinery and affecting licensing of dairy products. The processor shared:

"*My factory was completed in 2004. In 2005, I requested an electricity connection. Electrogaz (now REG) asked me to buy the cable while they provided the poles. Since then, the supply has been weak. I bought a pasteuriser on loan but have never used it. As a private investor, I face unfair treatment, while MCCs receive proper connections, free of charge. REG says I must buy my own transformer."(interview with processing plant manager 13, 2022).*

A general pattern emerging from the interviews is that geographical proximity plays a key role in the effectiveness of interactions between REG and DVC actors. However, the above case shows that proximity does not guarantee equitable service provision, particularly for privately initiated plants. While this case illustrates difficulties related to connection quality and infrastructure costs, several actors in Rubavu and Nyabihu districts reported receiving quick responses from REG, which they attribute to the nearby REG offices located in Rubavu City and Nyabihu District Headquarters Town. As one processing plant manager noted:

"We discuss power cut issues with REG, and they respond quickly to resolve them. REG has an office just 2 kilometres from this

[9] Earth faults, including those caused by lightning, falling trees, and moisture infiltration into underground cables, account for 39.42% of all power outages. In contrast, overcurrent events represent 33.27% of outage causes during the same reporting period (REG, 2024).

[10] RWF: Rwandan Franc is the official currency of the Republic of Rwanda.

[11] In this study, we used the official exchange rate published by the National Bank of Rwanda (BNR: Banque Nationale du Rwanda) on June 15, 2026. On that date, one United States dollar (USD) was equivalent to 1,469.705 Rwandan francs (RWF) (BNR, 2026)

location."(Interview with processing plant manager 4, 2022).

In contrast, in Burera District, where the REG office is over 36 km away[12], face-to-face interaction is limited. While MCCs, processors, and REG communicate by phone, the distance hampers the delivery of timely technical support. Maintenance staff must travel this distance, often requiring vehicles or motorcycles, which delays response times. This suggests that telephone and email communications cannot fully substitute for geographic proximity when maintenance and repair services require the physical presence of REG technical personnel. Consequently, long distance weakens the effectiveness of interactions among DVC actors and REG.

Electricity issues also affect the distribution of dairy products in Musanze, Rubavu, and Kigali cities. Wholesale agents and distributors, working with both SMEs and large-scale processors, report that outages compromise cold-chain integrity. Spoiled dairy products cannot be returned, straining producer-seller relationships, as contracts rarely account for losses due to power interruptions.

4.4.2. *Affordability*

The affordability of the electricity grid and the costs of repairing other off-grid energy systems can significantly impact the operations of dairy processors in various ways. The coevolution of the two sectors and the expansion and maintenance efforts have helped address these affordability challenges. Collaboration between REG and MINAGRI, within the framework of the RAB-PASP and RDDP projects, has also helped reduce these impacts. Access to the grid has contributed to affordability at the MCC level, significantly impacting operational costs and financial sustainability. As the EADDP report (2008, p. 34) noted in 2008:

> *"Most MCCs are situated in areas without electricity, necessitating reliance on generators to chill milk, which incurs an average monthly cost of 160,000 RWF (≈USD 108.86 USD), including fuel and maintenance. This expense can be considerable and, in some months, surpass the monthly cost of staff salaries* (TechnoServe Rwanda, 2008)*"*

Respondents state that grid access has reduced the financial burden of off-grid energy systems and report that the current grid electricity bill ranges from 75,000 to 100,000 RWF (≈51.03 to ≈68.04 USD). Processors report the highest electricity costs. For instance, BP1 states that it pays 1,000,000 RWF (≈680.40 USD) per month. While access to the grid has reduced the cost of electricity, unreliability and the need for backup systems from more expensive energy sources still undermine economic viability (see Table 7 for details).

Despite improved reliability from infrastructure upgrades like substation construction, processors in Rwanda's DVC continue to face high electricity costs and frequent outages. These disruptions necessitate reliance on backup generators, which significantly increase operational expenses and result in economic losses. As one processor explained:

"*The use of fuels increases the cost of our energy use… our generator is always on standby*." *(Interview with processing manager1, 2022).*

Electricity tariff policies also shape affordability. MCCs are classified as industrial users by RURA, which segments them into small, medium, and large categories, with rates of 134 (RWF (0.09 USD/kilowatts-hour (kWh), 103 RWF (≈07 USD)/kWh, and 94 RWF (≈0.06 USD)/kWh, respectively. Small-scale processors face higher demand charges, which vary by time of use (off-peak, shoulder, and peak hours), in addition to a fixed monthly service fee of 10,000 RWF (≈6.80 USD). This complex pricing structure places a disproportionate burden on MCCs, especially those with lower milk collection quantity, making electricity less affordable and threatening their long-term viability.

Table 7
Affordability and energy issues at different DVC actors and locations

DVC actors	Location (district)	Financial constraints	Electricity issues
MM1, RM1, NM3	Musanze	Severe financial constraints due to high repair costs and lack of investment in backup systems	Increased operational expenses during power outages lasting more than one hour
RM2	Rubavu	Management of generator fuel costs within operations, despite severe financial constraints and lack of investment in backup system	Increased operational expenses during power outages lasting more than one hour
RM3	Rubavu (open grazing zone)	Reliance on loans for repairs, exacerbating financial strain	
NM2	Nyabihu (open grazing zone)	Management of generator fuel costs within operations	Lack of solar power limits potential cost savings; uses LPG for water heating
MM2	Nyabihu	High generator costs and infrastructure upgrade expenses	Limited policy support from REG
NM1	Nyabihu		Solar integration and reliable grid supply, reducing long-term costs
BP1	Burera	High electricity bills of 1,000,000 RWF per monthStrained cash flow, affecting ability to pay salaries and suppliers	Additional costs for backup fuel
NP2	Nyabihu	Monthly cost of 50,000 RWF for electricityLeads to significant milk losses and related financial losses	Lack of backup generator,High vulnerability of operations during power outages
RP1	Rubavu	High operational costs due to unreliable electricity supplyFurther increases in economic losses	Uses of expensive firewood
NP1	Nyabihu	Difficulty to pay electricity bills, records of monthlyFuel cost reduced since improvement in reliability; recent substation construction has reduced expenses	Heavy reliance on diesel generators during outages, consuming 200-300 litres per day

Sources: Interviews and reviews of secondary materials.

4.4.3. *Maintenance*

Maintenance practices across MCCs vary based on financial capacity, equipment size, and proximity to REG, all of which influence sustainability. For internal electrical systems, like milk pumps and compressors, MCCs rely on external technicians from Kigali, Musanze, and Rubavu. This dependence causes delays, higher costs, and frequent downtimes, as MCCs lack in-house technicians. These challenges reduce operational efficiency and increase vulnerability to equipment failures and milk losses.

Financial stability plays a crucial role in the maintenance, significantly impacting their overall stability. Those with stronger finances, such as three in Nyabihu and one in Rubavu District, particularly in open grazing zones, can invest in regular repairs and infrastructure upgrades. Their consistent milk volumes (over 1,000 litres per day) and collaboration with the REG help to minimise service disruptions.

In contrast, financially constrained MCCs face serious challenges. In Rubavu District, one MCC struggles against competition from the informal milk market, while another in Musanze cannot afford to maintain its equipment. The MCC president noted:

"*The churning machine, which uses solar electricity, has stopped working because it requires more maintenance."(interview with MCC president 6, 2022)*

[12] As this article is being finalised, the road connecting the MCCs, the processing plant, and the REG office in Burera District is being upgraded from gravel to asphalt. Once the upgrade is completed, it is expected to make REG's physical visits and technical interventions easier and more efficient.

This situation often leads to the abandonment of infrastructure, which limits value addition and reduces competitiveness.

At the processor's level, sustainable maintenance is crucial to the coevolution of electricity supply and the DVC. Processors relying on an unstable grid face high cost of repair and replacement due to voltage fluctuations. One processor noted frequent replacements of fuses, cables, and milk pumps. BP1 and RP1 regularly experience equipment failures linked to low power quality. These disruptions lower product quality, delay deliveries, and reduce overall processing efficiency. At RP1, limited finances hinder routine maintenance, leading to more frequent breakdowns and a weakening of its market position, which in turn affects smallholder farmers who depend on consistent payments.

In contrast, processors NP2 and NP1 in Nyabihu District have adopted proactive maintenance practices. NP2 maintains pasteurisers and compressors regularly to reduce downtime. NP1 employs full-time engineers to service in-house electrical and production systems. It also benefits from insurance coverage for major components, such as transformers, which lowers the burden of unexpected repairs. A more stable electricity supply, enabled by the recently built Nyabihu Sub-station, further supports its operations. The difference between reactive maintenance at BP1 and RP1 and proactive strategies at NP2 and NP1 illustrates how electricity reliability influences maintenance approaches. In turn, these practices affect DVC performance, as consistent processing is essential for delivering high-quality dairy products and sustaining farmer livelihoods.

4.5. Comparison of reliability, affordability and sustainable maintenance across the districts

While electricity reliability, affordability, and maintenance are broadly similar across districts, they vary significantly within them. Key factors influencing reliability include the age of the electricity network, government interventions, relationships with REG, and the financial and managerial capacity of actors, often linked to milk collection volumes.

In Nyabihu, MCCs previously far from the grid now benefit from medium-voltage lines and nearby transformers, resulting in reliable power and minimal power cuts. A large processor in an industrial zone also benefits from a new substation. However, this did not prevent the company from relocating to Kigali, where its proximity to its parent company, Inyange Dairies, allows for better resource sharing.

In Rubavu, REG's response to outages can take up to 24 hours. During such events, MCCs must quickly coordinate with processors or sell milk to traditional processors ("kitchens") at a reduced price, sometimes incurring losses of around 50 RWF (≈0.03 USD) per litre. These losses have discouraged participation in the upgraded DVC, as evidenced by the abandonment of modern processing at RM 3 (see Table 3). In Musanze and Burera, outdated networks continue to cause voltage fluctuation, suggesting that infrastructure upgrades have not fully resolved reliability issues.

Across all districts, better-resourced actors mitigate power issues by maintaining or replacing backup systems, such as solar panels and generators. Internal component maintenance is the most common challenge, typically handled by private technicians from Kigali and nearby cities, while REG manages external infrastructure repairs, including poles, cables, and transformers. Overall, while some MCCs benefit from improved infrastructure and responsive utility services, others remain vulnerable due to their systems' history and limited investment. The coevolution of the electricity and dairy sectors depends on targeted upgrades, reliable backup systems, and effective utility management.

4.6. Changes in flow between sectors

This section discusses the outcomes of the coevolution of electricity and DVC, focusing on changes in the flow of milk, information, funding, and electricity demand driven by the DVC sector. These changes have connected different locations and actors, increasing their relative proximity between cities and rural areas (see Fig. 5 for details).

Electrification and modernisation have transformed the flow of milk and dairy products. Reliable electricity enabled large-scale processors to introduce new standards for raw milk quality, such as bacterial activity counts using the Resazurin Reduction Test (RRT). Effective cooling and timely milk transport to MCCs enable suppliers to collect milk even days after farmers deliver it. This mitigates seasonal effects and improves milk quality, increasing the processing capacity of the large-scale processor from 5,000 litres per day in 2018 to 35,000 litres per day in 2023. The largest quantities of milk are sourced from MCCs in Nyabihu, Musanze, and Rubavu, thereby reducing reliance on the traditional unelectrified sub-VC. Cultural factors continue to influence milk production, but processors report no shortages. Product diversification has also been enabled, with large and small processors now producing pasteurised milk, cheese, yoghurt, and butter. Concerning challenges, SME processors face restrictions on polystyrene packaging, which limits product diversification. One expressed frustration that similar packaging is allowed for cheese imports from the Netherlands. They view Rwanda Environmental Management Authority's (REMA) inconsistent enforcement as unfair.

Regarding the flow of information, it has improved through structured meetings, training, and use of digital tools. MCCs share updates with government organisations, such as Rwanda Inspectorate, Competition and Consumer Protection Agency RICA and Ministry of Trade and Industry (MINICOM: Ministère du Commerce et de l' Industrie), on milk quality, pricing, and contracts, with support from NGOs and government agencies. Digital adoption varies: MCCs in Nyabihu District utilise computers, whereas those in Musanze and Burera districts rely on manual records. Communication with REG has improved, especially during outages. The large processor utilises advanced digital systems for machinery control, while others employ smartphones and the internet for coordination and power management.

Regarding the flow of finance, electrification has enabled reliable financial transactions and expanded access to banking services. All MCCs have bank accounts, improving transparency and audit readiness. Decentralised banking has reduced transport costs and improved access to credit. Milk pricing has improved, rising from 50 RWF (≈0.03 USD)/l to 440 RWF (≈0.29 USD)/l over 15 years, with MCCs retaining a portion for operational costs. Challenges remain: some suppliers lack access to mobile banking, and MCCs are unable to offer collateral for loans. Payment timing varies, with some kitchens offering faster payments, which can sometimes divert supplies from MCCs. Some SMEs face challenges, such as tax penalties.

These evolving flows highlight the interdependence among milk producers, MCCs, processors, and urban consumers, facilitated by infrastructure improvements and institutional coordination. Electrification plays a critical role, not only in supporting milk quality and processing but also in enhancing transparency, innovation, and financial inclusion. Generally, it reconfigures the DVC by drawing rural and urban actors into closer relational proximity, thus laying the groundwork for further integration and innovations.

4.7. The influences of the DVC network on the electricity sector

Rising rural demand is influencing electricity sector policies. Comparisons across actors show interdependency: in areas with positive engagement from REG, electricity use has increased due to sustained machinery operation. Conversely, negative or delayed REG responses have reduced usage and demand by increasing operational costs. For instance, MCCs spend approximately 75,000 RWF (USD 51.03) per day for single daily operations and 150,000-300,000 RWF (USD 101.91-203.82) per day for twice-daily operations. Likewise, dairy-processing SMEs incur daily operating costs ranging from 200,000 to 1,000,000 RWF (USD 136.08-680.40). The large–scale processor's monthly electricity bill is estimated at 2,000,000 RWF (≈1,360.81 USD), based on

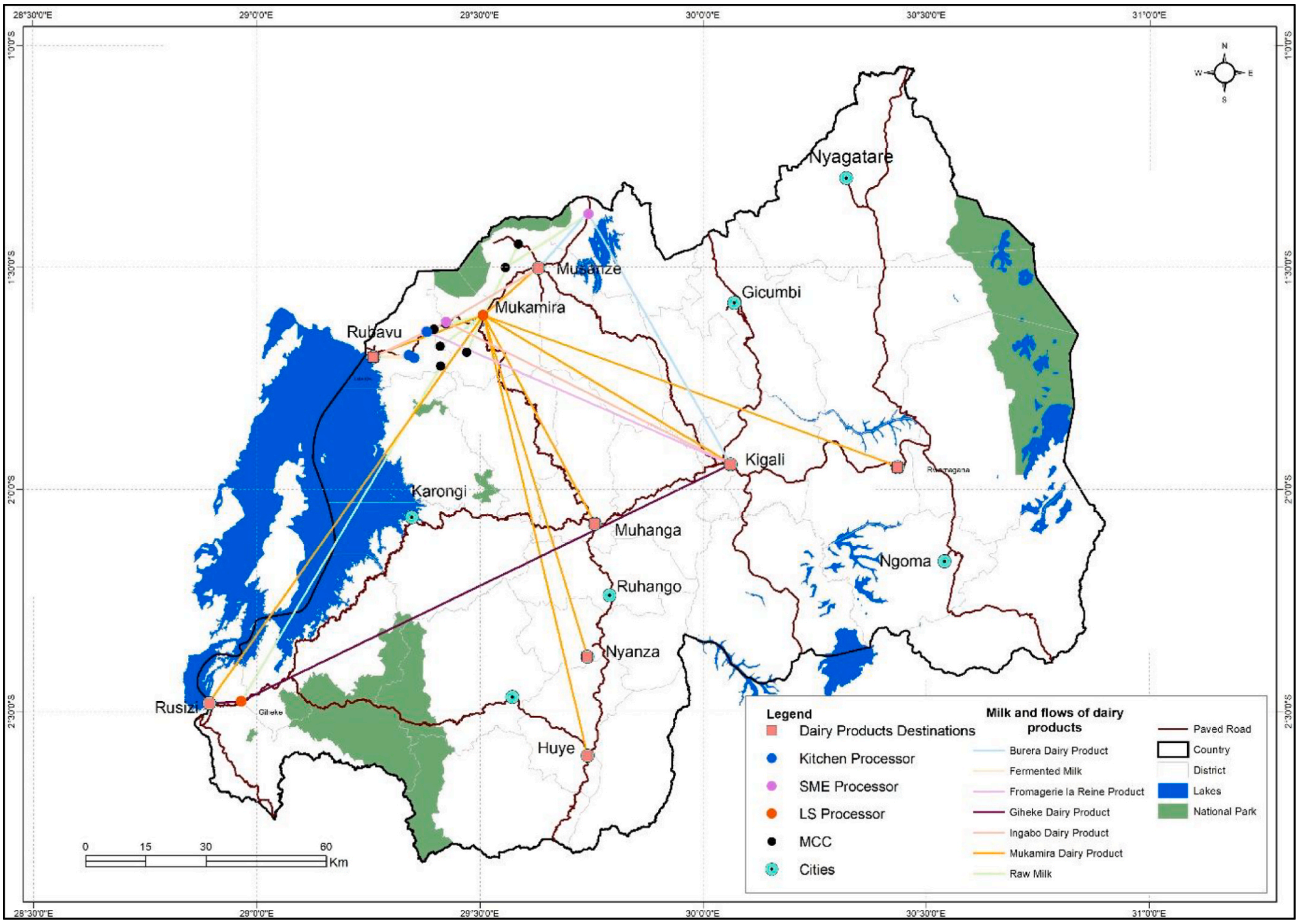

Fig. 5.

interview data. However, the billing records indicate an electricity cost of 6,000,000 RWF (≈4082.45 USD), corresponding to about 37,890 kWh of electricity consumption. This consumption reflects the energy-intensive nature of industrial processing in the rural context. Nyabihu District exhibits a higher demand due to the presence of two MCCs operating twice daily, as well as SMEs, and a large-scale processor. Burera District's SME processor averages 700,000 RWF (≈4756.28 USD) in reported electricity consumption. Seasonal variation, especially during the rainy season, increases electricity use.

The DVC's electricity demand is also driven by the spatial expansion of the cold chain, supporting the distribution of pasteurised milk, refrigerated cheese, fermented milk, and yoghurt. Fridges in distribution points and mini markets contribute significantly to consumption. Operating a cooling tank for industrially pasteurised milk costs about 30,000 RWF (20.41 USD), and a fridge costs 20,000 RWF (13.60). However, UHT milk does not significantly affect electricity demand because its Tetra Pak packaging allows it to be stored without refrigeration under Rwanda's temperate tropical highland climate conditions[13].

5. Discussion

This study examines how electrifying DVC contributes to rural transformation, focusing on the synergies and tensions that arise at the interface of the electricity and dairy sectors. Guided by insights from Sustainability Transitions, economic geography, and African rural electrification scholarship, the analysis explored how industrialisation and electrification co–evolve across the upstream and midstream stages of the DVC.

The DVC remains central to Rwanda's rural development agenda because many small–scale farmers depend on milk for income, food security, and market participation. While milk provision alone cannot eliminate undernutrition (Mpatswenumugabo, 2024), electrification enhances food safety, stimulates rural economic activity, and generates "anchor loads" that support grid expansion (IRENA, 2021; Osunmuyiwa & Ahlborg, 2022).

Empirical evidence from four districts, representing around 20% of national MCCs, shows that the DVC and national grid have expanded together, gradually aligning local practices with national policy objectives. However, the pace and character of this co–evolution vary across districts due to differences in local resources, institutional capacity, and historical investment patterns. Consistent with Edmondson et al. (2019), the findings highlight feedback loops between policy priorities, political interests, and socio–technical change. The government's efforts to modernise the DVC, for example, helped align farmer expectations with national goals and supported the establishment of MCCs and processing units.

This transformation was facilitated by a broad coalition of actors, including MINAGRI, AfDB (African Development Bank), IFAD, REG, Heifer International, and districts, through projects such as PADEBL, RAB–PASP, and RDDP. Early dependence on off–grid diesel generators under PADEBL proved unsustainable, but later collaboration between dairy stakeholders and electricity providers enabled grid extension and

[13] Rwanda has a temperate tropical highland climate characterised by moderate year-round temperatures ranging from approximately 16°C to 28°C.

lowered electricity costs through cooperative arrangements. These partnerships strengthened emerging networks linking MCCs, processors, distributors, government agencies, and electricity providers.

Electrification allowed smallholder farmers to connect more effectively to modern dairy systems that enable product diversification, quality improvement, and more stable incomes. The DVC comprised four interconnected sub–chains at the time of the study, though a large share of milk[14] continued to flow through informal channels. ICT adoption has reinforced these linkages by facilitating financial transactions and improving coordination.

Results demonstrate that upgrading DVCs in a rural context can illustrate the transformative potential of electrification across agrarian and low-income countries where fragmented energy systems and agri-food VCs constrain rural economies. First, milk cooling practices increasingly align with quality standards set by processors, supported by quality testing, and compliance. Second, the integration of telecom and banking systems has accelerated rural financial inclusion, improving information flow and payment efficiency. These changes have strengthened rural–urban ties and expanded access to high–value markets. Yet electricity unreliability continues to undermine these gains. Spoilage at MCCs forces actors to discard milk or divert it into informal channels, weakening trust, reducing incomes, and reinforcing dependence on non–regulated routes.

Several intertwined challenges limit deeper coevolution. Low milk supply in some districts constrains MCC viability and reduces utilisation of electrified infrastructure. Milk diversion to informal markets, driven by inadequate cooling, delayed payments, price competition, and electricity instability, further limits formalisation. Cultural practices and long–standing informal sub–chains intensify these disruptions. Uneven adoption of digital tools restricts real–time data flows, while limited access to mobile banking and lack of collateral constrain investment in herd improvements and farm equipment. Because the DVC depends heavily on the national grid, outage and high prices of electricity have negative effects across the electrified segments of the DVC.

The results demonstrate a general pattern regarding the relationship between fixed location and relative proximity in the agri-food VC. Rather than being determined solely by fixed location in terms of either closeness to inputs (raw milk production) or to the market, upgrading trajectories are shaped by how infrastructure, connectivity, and governance arrangements (particularly privatisation) reconfigure spatial relationships and enable better flows between production zones and urban markets. In the case of Rwanda, large-scale processing plants were initially located within the milkshed based on government decisions aiming at increasing productive use of electricity. However, following privatisation, the relocation decision prioritised proximity to the urban market, leading to the concentration of large-scale UHT and pasteurised milk production in Kigali. The processor's capacity to transport milk from multiple MCCs to Kigali, enabled by the road network, cooling infrastructure, and rural milk aggregation systems, reduced the importance of maintaining the processing plants within the milkshed. As a result, fixed location became less influential in shaping the DVC's upgrading trajectories.

Reliable and affordable access to electricity and storage facilities remains essential for the transformation of agri-food VCs (Rob & Cattaneo, 2021). In this case study, electrification facilitated cooling, preservation and transportation of milk over longer distances, thereby extending material and financial linkages along the DVC. In this configuration, fixed location and relational proximity become complementary (Hategekimana et al., 2025). Yet this shift has distributional impacts. Relocating electricity–intensive processes to cities can reduce rural electricity demand, weakening incentives to maintain stable rural supply. It also accelerates rural–urban labour patterns, concentrating higher–value economic activities in urban centres and potentially undermining rural transformation objectives of agri-VCs upgrading (Cattaneo et al., 2022).

National and regional structural constraints continue to shape the co–evolution of the dairy DVC and electricity. Rwanda's limited land availability constrains dairy expansion, while low levels of FDI restrict growth in both sectors. Regional political shocks, such as Tanzania's import bans and Burundi's border closures, further expose vulnerabilities in cross–border trade. In contrast, Kenya and Uganda benefit from larger land endowments and higher FDI inflows, enabling them to scale up dairy production and integrate more effectively into global dairy networks (Abdulsamad & Gereffi, 2016; Van Campenhout et al., 2019). Rwanda's response has been to intensify production through zero–-grazing systems and to reorient growth toward export markets, supported by investments in domestic milk powder processing (Niyonzima et al., 2025).

Despite persistent constraints, the transformation of Rwanda's DVC is gradually converging with regional patterns observed in neighbouring EAC countries, particularly Uganda and Kenya. This suggests that targeted state interventions in sectoral coevolution, combined with private–sector and community participation, can drive incremental transitions in value chains from predominantly local systems toward regional and global integration (Gereffi & Sturgeon, 2013).

6. Conclusions

This study highlights the need for coordinated interventions to sustain and deepen coevolution between sectors. Integrating ICT tools and modern equipment into agri-value chain operations, building management capacity, and improving financial access enable actors to make more productive use of electricity. Modernising and electrifying informal sub–chains extend benefits to MCCs, processors, enhancing the country competitiveness in the agri-value systems. By strengthening collaboration among aggregation and storage actors, processors, and government agencies, the government, donors and electricity utilities play roles in enhancing electricity reliability and affordability. This stimulates the quality of agri-value chain products quality and trust among actors.

Complementary investments in roads, networks, and small–scale renewable energy systems such as solar–power, and biogas at farm level, improve product quality and economic benefits in off–grid or under–electrified areas. These integrated strategies are essential for reinforcing mutual development of the electricity and agri-value chain actors and practices.

This study has limitations in its treatment of community perspectives, particularly regarding the role of MCCs as intermediaries in enabling a just transition in the dairy sector. Greater attention to community-level dynamics would allow for a deeper analysis of how MCCs connect diverse social groups, including large-scale and smallholder farmers, as well as women, to address milk production constraints and poverty reduction through participation in the DVC transition. In addition, further research is needed on the integration of renewable energy technologies, such as biogas and off-grid solar systems, into DVC upgrading in Rwanda and elsewhere in the region. Examining these linkages would provide valuable insights into how energy transitions can be embedded within DVC transformation, thereby contributing to broader understanding of sustainability transitions in the Global South context.

CRediT authorship contribution statement

Sylvère Hategekimana: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation,

[14] Approximately 60–80% of milk in Rwanda is reported to be sold through informal channels (Abdulsamad & Gereffi, 2016; Habiyaremye et al., 2021). This aligns with our interviews, district reports, and field observations on volumes of traditionally fermented milk transported across the Rubavu (Rwanda)–Goma (DRC) border and sold in local restaurants..

Formal analysis, Conceptualization, Data curation. **Helene Ahlborg:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Jean Pierre Bizimana:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the corresponding author used Microsoft Copilot AI to improve the text's language and readability. After using this tool/service, the corresponding author, other authors, and the language professional reviewed and edited the content as needed, taking full responsibility for the publication's content.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoforum.2026.104798.

Data availability

Data will be made available on request.

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