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The Nairobi Off-Grid Cluster

From an energy failure to social and industrial innovation diffusion

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Abstract

Access to energy is one of the most significant challenge in Sub-Saharan Africa. Despite recent economic growth, a large share of the population still lacks access to electricity, particularly in rural areas where centralized grids are often economically and technically difficult. In this context, decentralized energy solutions, especially off-grid solar systems, have emerged as an alternative solution to expand energy access.

This thesis analyses the role of energy clusters as a mechanism that can facilitate the development and diffusion of decentralized energy technologies. Building on cluster theory and its evolution toward knowledge-based and innovation-driven systems, the study examines how geographical concentration of firms, institutions and supporting organizations can generate externalities, knowledge spillovers and collective learning processes that support technological development and market expansion.

The analysis focuses on the off-grid solar cluster that has developed in Nairobi, Kenya, which has become a key innovation ecosystem for decentralized energy solutions in Sub-Saharan Africa. By examining the interactions between firms, investors, institutions and international actors, the thesis explores how cluster dynamics can contribute to the growth of new energy markets in developing economies.

The findings suggest that energy clusters can play a crucial role in accelerating energy transitions by fostering innovation, reducing coordination costs and enabling the scaling of decentralized energy technologies.

Methodology

This thesis employs a qualitative research design based on a single case study. The research does not aim to measure the prevalence of a phenomenon across a large sample, but rather to gain an in-depth understanding of how and why a group of economic actors concentrated in a specific urban area, in this case Nairobi, has given rise to a configuration that can be traced back to the concept of an energy cluster, and to identify any deviations from the theoretical reference model presented in Chapter 1.

Nairobi represents the most mature and best-documented off-grid solar ecosystem in the literature and thus constitutes the most favourable empirical context for observing, with the highest degree of detail currently available, the dynamics of energy cluster formation in a development context, a phenomenon that, as discussed in Section 4.3, the literature on industrial clusters has so far explored only marginally. The case was not chosen for its statistical representativeness with respect to the universe of African off-grid markets, but for its ability to make observable a phenomenon that elsewhere would remain too embryonic to be analysed with the same level of detail.

Data collection was based entirely on secondary sources. Three types of sources were used, in order of priority: peer-reviewed academic literature (found through bibliographic search platforms such as Google Scholar, ScienceDirect, and Elsevier); institutional reports from multilateral organizations and specialized agencies (the World Bank, the International Energy Agency, the International Renewable Energy Agency, GOGLA, and the International Labor Organization); primary regulatory and institutional documents (2010 Kenyan Constitution and the 2019 Energy Act).

The analysis of the collected data followed a deductive approach: the Cluster Theory framework presented in Chapter 1 was used as an interpretive framework through which to systematically examine the evidence gathered on the Nairobi case in Chapters 2 and 3. In practice, each empirical element documented in the case study was compared with what the theory would predict under ideal conditions, with the aim of identifying, as discussed in Chapter 4, not only the confirmations but, above all, the discrepancies between the two levels, which constitute the main analytical contribution of this thesis.

This research design has methodological limitations. The exclusive reliance on secondary sources, in the absence of direct interviews with stakeholders in the ecosystem, means that some of the dynamics discussed, particularly those related to workforce mobility between firms and informal relationships within the cluster, have been reconstructed indirectly, through the lens of other researchers' studies, rather than observed directly. Furthermore, the decision to analyse a single case, while justified by the exploratory nature of the research question, limits the possibility of generalizing the results to other contexts without further verification. The conclusions of this thesis should be understood as a contribution to cluster theory applied to a new empirical domain, not as a statement valid for the entire universe of African off-grid markets. Finally, the rapidly evolving nature of the sector under analysis implies that some of the quantitative data discussed, particularly those related to employment, represent a snapshot of the reference period covered by the consulted literature, not a measure that remains stable over time.

Generative artificial intelligence was used as a supporting tool during the preparation of this thesis. Calude (Anthropic) was used mainly for the revision and optimization of text to improve clarity, coherence, and structure, as well as for limited support in drafting and reformulating individual sentences. It was also used to assist with the presentation of selected charts, diagrams, and illustrative figures used to communicate the conceptual framework and results. AI support was used across different stages of the thesis, including the literature review, methodology, case analysis, and discussion. It was not used to replace the collection or interpretation of primary data, the selection of academic sources, quantitative calculations, or the author's analytical conclusions. All AI-assisted content was reviewed and reworked by the author and, where factual or analytical claims were involved, checked against the original academic sources, institutional datasets, interview material, and underlying calculations. The author retains full responsibility for the accuracy, interpretation, and scientific integrity of the final work.

Chapter I Industrial Cluster Theory and Economic Foundations

1.1 The concept of cluster

Firm performance doesn't depend solely on its individual action, the success is affected by an environment of complementary firms, infrastructure and institutions around it.
One geographically proximate group of interconnected firms and associated institutions in a particular field, linked by commonalities and complementarities, is called "cluster".
The origin of the concept of Industrial cluster lies in the book "Principles of economics" from Alfred Marshall (1890), where the idea was introduced, without using the term cluster, through the identification of the "Marshallian externalities", which are examined in detail in the Section 1.1.

After the First World War Marshall, published the book "Industry and Trade" in 1919, analysing the effects of the conflict on the industries, trade and labour organization. Even if the book is a detailed analysis of early 20th century's capitalism, Marshall state an important concept for the Cluster Theory and the importance of having an interconnected environment: "The broadest and in some respects most efficient forms of cooperation are seen in a great industrial district where numerous specialized branches of industry have been welded almost automatically into an organic whole" (Marshall, Industry and Trade, 1919).

The literature suggests that, although the century, the Marshallian externalities are still able to explain the superior value and productivity generated by firms located in a cluster, compared to the isolated ones, even in advanced sectors. This is possible because they concern mechanisms which remain strongly localised, even if goods and information circulate globally.
In the evolution of the modern Cluster Theory, the Marshallian externalities are reinterpreted as spillover, shifting the focus from static and microeconomic trends to dynamic and systemic processes. The difference is the nature of the benefits: in Marshall the externalities are not intentional and not internalized, generated by the geographic proximity, with a focus on efficiency, production costs and industrial organization; in the modern Theory the spillovers are a dynamic and systemic concepts, with cumulative and

evolutive benefits, linked to learning and innovation, with a focus on knowledge diffusion, capability building and social and institutional impacts.
It can be observed that spillover replaces externalities, maintaining the core conceptual basis, shifting the focus from collateral effect to spatially embedded diffusion processes, facilitated by physical proximity, continuous interactions and labour mobility (Sforzi, 2015).
Contemporary literature distinguishes between industrial spillover, regarding productivity, innovation and capabilities, and social spillovers, regarding inclusion, social capital and collective learning (Guiso & Schivardi , 2004).

An important theoretical contribution, that shifts the cluster focus from productive concentration to socio-economic system embedded in the territory, is provided by Giacomo Becattini, who in 1990 published "The Marshallian Industrial District as a Socio-Economic Notion. Industrial Districts and Inter-firm Co-operation in Italy". This study play a key role in the history of the industrial Cluster Theory because introduce the social and institutional dimension of a cluster, identifying it as a socio-territorial entity characterized by a community of people and a population of firm (Becattini, 1990). Becattini contribution introduces in the framework new elements, such as institutions, culture, and social capital. With his studies the territory is no more only identified as where the cluster is located but becomes the element which produces it. Its interpretation enables linking the cluster to not just the industrial spillovers that come from it, but to the social spillover too.
According to Becattini (1990) a cluster doesn't necessarily have to be manufacturing-based, instead the concept is extended including not only firms, but also services, institutions and non-profit actors embedded in the local community. In this perspective cluster can also operate in developing contexts where the territory and its actors play a crucial role in fostering collective learning processes, coordination and local development (Becattini, 1990).

The modern definition of Industrial Cluster is given by Michael E. Porter:
"Cluster are geographic concentrations of interconnected firms and institutions in a particular field. Cluster encompass an array of linked industries and other entities important to competition. They include, for example suppliers of specialized inputs such

us components, machinery, and services, and providers of specialized infrastructure. Cluster also often extend downstream to channels and customers and laterally to manufacturers of complementary products and to firms in industries related by skills, technologies, or common inputs. Finally, many clusters include governmental and other institutions – such us universities, standard-setting agencies, think tanks, vocational training providers, and trade associations – that provide specialized training, education, information, research, and technical support." (Porter, Clusters and the New Economics of Competition, 1998)

With this perspective Porter linked to the Cluster Theory the elements of competition, innovation and productivity that has become fundamental for its identification, introducing also the crucial concept of co-opetition (competition & cooperation).

The literature suggests that, over time, several authors have analysed cluster structures and operations, outlining a clear and comprehensive framework, that is now at the core of the Cluster Theory. Drawing on the literature industrial clusters are commonly characterized by a set of recurring features, which may manifest with different intensities depending on the context:

- Geographical proximity of the firms, mainly SMEs. Not meant as zero distance but as ease of interaction.
- Industry or supply chain specialization, to have a homogeneous and linked value chain with technological and sectorial coherence.
- Dense network of relationship within the district: collaboration between firms, but also competition based on quality and innovation. Not as perfect cooperation but as continuous interactions.
- Presence of specialized supplier, advanced services, dedicated infrastructure and support institutions (associations, education, and research).
- Socio-cultural identity which fosters trust, cooperation, and shared norms, and which facilitates knowledge sharing. Not as cultural homogeneity but as trust mechanisms.

Geographical proximity is crucial in knowledge-based economies because most of the knowledge is tacit, so require frequent face-to-face interactions, relying on trust

relationships and institution difficult to “virtualize” (e.g. Chamber of Commerce, which organizes services, events and support centres in the territory). The digitalization affects this characteristic, due to new digital tools that reduce the distance-related costs supporting “virtual proximity”, not replacing entirely the effect of physical proximity and tacit knowledge. Studies on Cluster demonstrate that despite the intensive use of digital tools the stronger relationships and knowledge spillovers are consolidated through face-to-face meeting and local interaction (Atkin, Chen, & Popov, 2022).

Cluster characteristics generate positive externalities, such us specializes labour market and supply chain, knowledge spillover and collective learning, which make it a self-reinforcing system over time, able to adapt to technological and market change, generating innovation and protecting the link between territory, community and productive structure.

Taken together, the Cluster Theory provide a flexible analytical framework that enables the interpretation of industrial development phenomena across sectors and contexts, including in areas with infrastructural deficiencies, institutional constraints, and development conditions. The framework will be used in this paper to analyse how cluster dynamics emerge and operate in environment characterized by persistent structural constraints and infrastructural gaps.

1.2 Cluster economics

Beyond their definitions and structural features, the economic relevance of industrial clusters relies in the “Marshallian externalities”, the mechanisms through which this configuration generates productivity gains, innovation and competitive advantage:

- Labour market pooling.

  A cluster generates a highly specialized local labour market, where firms can easily find workforce with sector-specific capabilities and know-how, and vice-versa workers find employment opportunity without the need to migrate. The advantage comes from the simultaneous presence of multiple actors in the same area.

  This externality reduces job-matching costs and contributes to the accumulation of human capital within the specific industry.

- Specialized suppliers.

  The concentration of firms within a cluster generates sufficient demand to support the need of specialized suppliers, which provide tailored service and complementary capabilities. The suppliers aren't designed to support a single firm, but the cluster. All the firms in it benefit from its presence even if they didn't bear initial costs.

  This externality leads to higher productive efficiency and continuous incremental innovation, facilitating a reduction in transaction costs.

- Knowledge externalities.

  Being the firms specialized in the same industry, knowledge circulates more easily within the cluster, particularly when it is tacit: "The mysteries of the trade are in the air" (Marshall, Principles of Economics, 1890). Knowledge diffusion is not fully internalized because those who generate it don't control who can benefit from it. The transfer happens through different mechanism, such as labour mobility, informal interactions and imitation.

  This externality accelerates innovation and reduces learning costs, increasing the overall productivity.

In globalization epoch, where capital, goods and information move freely, the geographic location is not losing importance, instead becomes a crucial factor that enables spillovers. A sustainable competitive advantage relies in local factor which are difficult to replicate remotely. There are different economic mechanisms that enable the cluster to become more productive, innovative and resilient compared to isolated firms.

The productivity is the fundamental determinant of nation's standards of living (Porter, Location, competition, and economic development: Local clusters in a global economy, 2000). The economic mechanisms that enable productivity are several, but can be synthetised in externalities, economic spillovers, agglomeration economies, and co-opetition.

Critical for the success of a cluster are its ground conditions:

- Flexibility. In order to answer to growing complexity in global markets.
- Outsourcing. Modulatiry and technical fragmentation of production.
- Innovation. Increasing knowledge and capabilities intensity the competition.

In the externalities and economic spillover perspective a crucial factor is the geographic proximity. This factor refers to the physical proximity between firms, supplier, customers, employees, and institutions in a delimitated area. This factor enables firms within the cluster to reduce costs due to the concentration of supplier and specialised services, which enables lower transport cost and higher reliability of supplies. The sharing of infrastructure for logistic, education, research and business services facilitate the exploitation of external economies of scale, on input and service supplied from outside. In this context an important actor are the Institutions, specifically the economic ones that provide the financial environment on which an industrial entrepreneurial net can bear and grow. Bank and financial agent provide the capital needed to sustain the cluster and develop its innovation, crucial for the sustainability of the environment. Also, University and Technical educational institution play a vital role creating an educated context, which can ensure a specialised labour market on one side and providing researching activities that participate in generate new knowledge on the other side, useful for the cluster in order to be alto to innovate and survive.

Formal, such as co-developed R&D project or sectorial association, and informal interaction enable collective learning on technologies, markets, and regulation, facilitating knowledge diffusion, generating spillovers that increase the ability to innovate in co-located firms. Geographical proximity enhances these channels making them more frequent, facilitating the transfer of tacit know-how.

Agglomeration economies that are generated in the concentration of complementary firms, lead to the rise of the production of each firm thanks to the specialised labour pooling, local supply chains and circulation knowledge. Studies about agglomeration economies demonstrate that firms within a cluster have higher productivity levels and intensity of R&D than similar isolated firms (Andersson , Larsson , & Wernberg, 2019). Combination of lower mean costs, rapid access to qualified inputs, and faster learning processes allow cluster's firms to better compete on prices, quality and time-to-market. A particular element of cluster is the coexistence of intense competition and selective cooperation, due to firms compete on product and efficiency, collaborating on education, R&D, and infrastructures. The competitive pression push a continuous technological and organizational upgrading.

The singularity of the environment makes the cluster able to absorb eventual shocks, technological or market's ones, increasing its resilience. Feature, which Isolated firms are lacking.

While these economic mechanisms explain how clusters enhance competitiveness and resilience, their functioning is strongly shaped by the broader economic and institutional context in which clusters are embedded. The following Section examines how cluster dynamics operate in developing countries, where structural constraints and market imperfections significantly influence their evolution.

1.3 Cluster in developing countries

Clusters are not closed systems exclusive to develop countries based on local exceptionalism, but organizational mechanisms through which the globalization has materialized in the territories. Valeria Giacomin in his work "A Historical Approach to Clustering in Emerging Economies" addressed the topic to understand the importance of clusters in developing countries.

Classical literature describes clusters as autonomous entities driven by local factors. Valeria Giacomin (2017), on the other hand, explains how different clusters are integrated into external networks and structures, acting as "operation centres" of attraction for capital, know-how, and inputs from outside.

Accordingly, clusters in developing countries can be seen as structures of globalization, linking frontier territories to global markets, which competitivity relies on both local and external resources. This picture better explain continuity, transformation, and competition between clusters in different areas.

In latecomer [1] economies these "operation centres" channelled capital, technologies, organizational standards, and international markets, becoming, in most cases export or touristic hubs and agricultural export districts.

Giacomin (2017) work is critical to understand how in developing countries' clusters persist and grow, but in order to understand why they emerge one relevant research is "Coordination Failures, Clusters and Microeconomic Interventions" from Rodríguez-

[1] An economy that is late to the process of industrialization and development compared to the first movers.

Clare (2005). This work analyses the failure of pro-market's reform in Latin America to generate sustained growth, proposing microeconomic interventions to overcome coordination failures of cluster and sectors.

Rodríguez-Clare's (2005) explain why in developing countries the market is not able to attract all the actors needed to develop one industry. The author argues that firms do not invest due to the lack of infrastructure, suppliers, specialised labour market, and regulation. In this context a cluster can born as spontaneous answer, enabling the concentration of firms and actors reducing risks and facilitating coordination. This perspective is particularly suitable for developing countries, which often face market failures.

Building this type of environment in contexts without solid foundation often clashes with the necessity of upgrading [2]. The element that concentrated firms better perform than the isolate ones is not enough, upgrading is crucial for clusters' long-term growth, because allow to avoid the risk generated by the concentration of resources and efforts only on low added value function. For example, in developing countries especially, firms in a cluster are often "low-cost performer", pushed by external actors that exploit this element to generate economies of scale; this element is profitable in a short-term strategy, but faces challenges due to easy replaceability with more convenient countries that compete on price reductions.

In this perspective upgrading must take place on different fronts:

- Process upgrading. Push the specialization of the production of one product, in order to become more efficient.
- Product upgrading. Implement the production of higher range and more complex products.
- Functional upgrading. Improve the business-related activity, such us marketing and logistic.
- Inter-sectoral upgrading. Shift towards related sectors, but more complex and lucrative.

[2] Upgrading: upgrade to a newer version or improve something compared to the previous state (Dictionaries, nd; Pietrobelli & Rabellotti, 2008).

This process is not easy to implement due to different challenges that has to face. Due to the lack of a stable and developed markets in developing countries, many clusters' firm are part of a global value chain (GVC) of major internation buyers, which strictly monitor the production and often the access to the market. Cluster's firm in this perspective remain production suppliers with weak bargain power. Institutional actors should play an important role to foster culture and knowledge that enables and support the growth, but often in these countries' universities, technological centres, financial institutions and agencies not provide advanced services suitable for upgrading requirements. The context is further penalized by the nature of firms: small, low capitalization, and family-owned with low investment in R&D and education. (Gancarczyk & Bohatkiewicz, 2018)

External actors and global linkages on the other side are one of the main drivers behind the creation of clusters, their operation, and the generation of upgrading trajectories. In development contexts public policies, international investors, multinational enterprise, ONG, development agencies, and sovereign institutions, combined with GVC contracts, joint-venture, and cooperation program, are able to bring capital, technologies, organizational standards, and access to foreign markets that a local cluster, alone, would struggle to achieve. Here particular attention must be dedicated to the relationship built among the actors, because an open and collaborative partnerships enable the transfer of knowledge and local involvement, helping the cluster to upgrade, in contrast of a hierarchical relationship where the cluster's firms remain low-cost performer.

Joint programs between global firms, associations, and local universities can strengthen skills within the cluster, making firms more autonomous in the long term. The cluster thus becomes a recognized node in the global supply chain, with regular flows of orders, services, and people. (Pietrobelli & Rabellotti, 2008)

1.4 From industrial clusters to energy clusters

M.E. Porter in his work "Location, Competition, and Economic Development: Local Clusters in a Global Economy" (2000) shows how Cluster are critical not only in manufactural sector, but all over industries. Clusters are cross-sectoral, but linked to the coexistence of innovation, interconnection and specialization.

Sovacool (2016) assess the energetic transition without talking about energy cluster. He framing the long-term process highlighting the critical role of innovation, institution, and coordination. From this perspective the energy sector is particularly suitable for the raising of cluster.

In order to understand the neutral nature of cluster we can assess the EU panorama, which show how over the decades have emerged ecosystem in a homogeneous distribution.

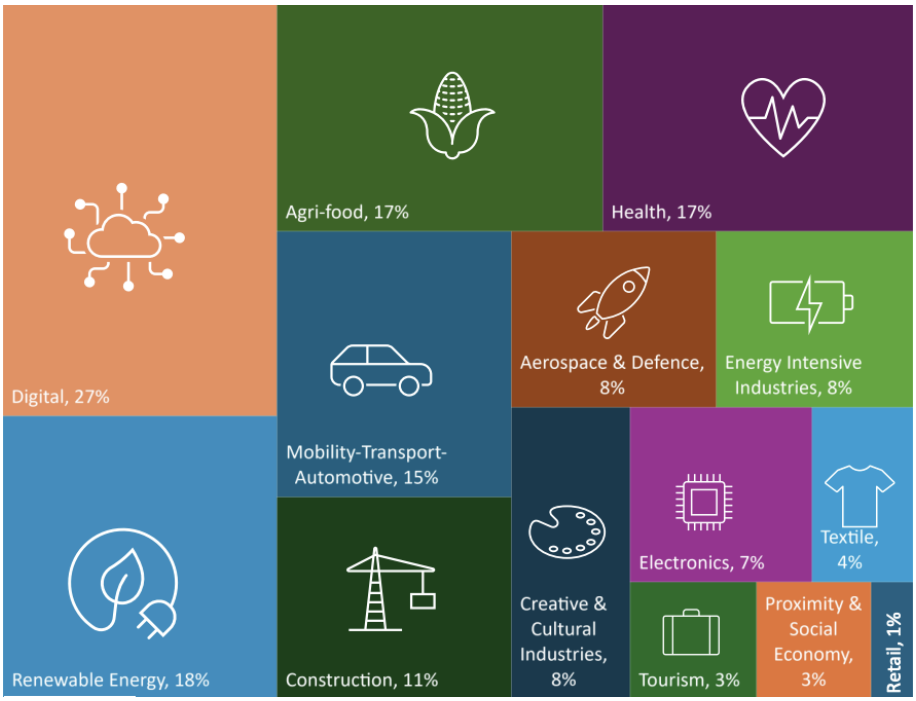


Figure 1: European Cluster Collaboration Platform (ECCP), data extracted on 21 December 2023 [3].

Figure 1 shows the cluster distribution across different EU industrial ecosystems. Analysing it we can see how Renewable Energy the second biggest ecosystem is, due to the characteristic that made it a natural context for cluster rise and proliferation: knowledge-intensive, capital-intensive, and innovation driven.

In this industry, energy firms, technologies provider, universities, institutions, and investors must work together to generate knowledge spillover and built complex technologies, where learning process play a key role. The energy transition and its

[3] (European Commission, 2024)

digitalization needs are generating new business model that push countries to develop energy innovation clusters.

As highlighted by Geels (2004), energy systems can be understood as socio-technical systems characterized by the interaction of multiple actors, including technology providers, infrastructure operators, regulatory bodies and financial institutions. In this context, the development of a dense network of specialized and complementary actors becomes a necessary condition for the functioning of the system, rather than a simple efficiency-enhancing factor.

The application of Cluster Theory to energy sector allows a reinterpretation of the classic Marshallian externalities. Labour polling, differently from manufactural industry, where the workforce is highly specialized in the same sector, involve the development of much more hybrid ad interdisciplinary capabilities and know-how. The sector requires a wide range of professional profiles, including energy engineers, installation technicians, software developers (e.g. in smart grids and IoT), project managers, and regulatory experts. The geographic concentration of these competences facilitates the matching between firm and qualified labour, supporting the accumulation of specific capabilities.

Complementarily the presence of specialized suppliers assumes (Geels F. W., 2004)a crucial role in the development of energy cluster. Unlike traditional industrial district, where suppliers mainly provide intermediate goods, energy clusters rely on a diversified supply chain, including technological providers, infrastructure developers, and financial actors. The concentration of these actors enables the access to critical inputs more rapidly, reinforcing the competitiveness and development of the cluster.

In this perspective, energy clusters represent an analytical framework to understand how innovation, entrepreneurship and infrastructure development interact in the energy sector. This framework is particularly relevant in developing economies, where clusters can facilitate the emergence of new energy markets in contexts characterized by infrastructural constraints and institutional gaps.

Chapter II The Energy Context in Sub-Saharan Africa

2.1 Geopolitical and economic dimensions

Since the beginning of the 21st Century Sub-Saharian Africa has experienced significant economic growth, driven by the sustained GDP increase of several countries of the area. This development relies on sector such as oil & gas (Nigeria), the expansion of services, especially for software (Kenya), and agriculture (Ethiopia).

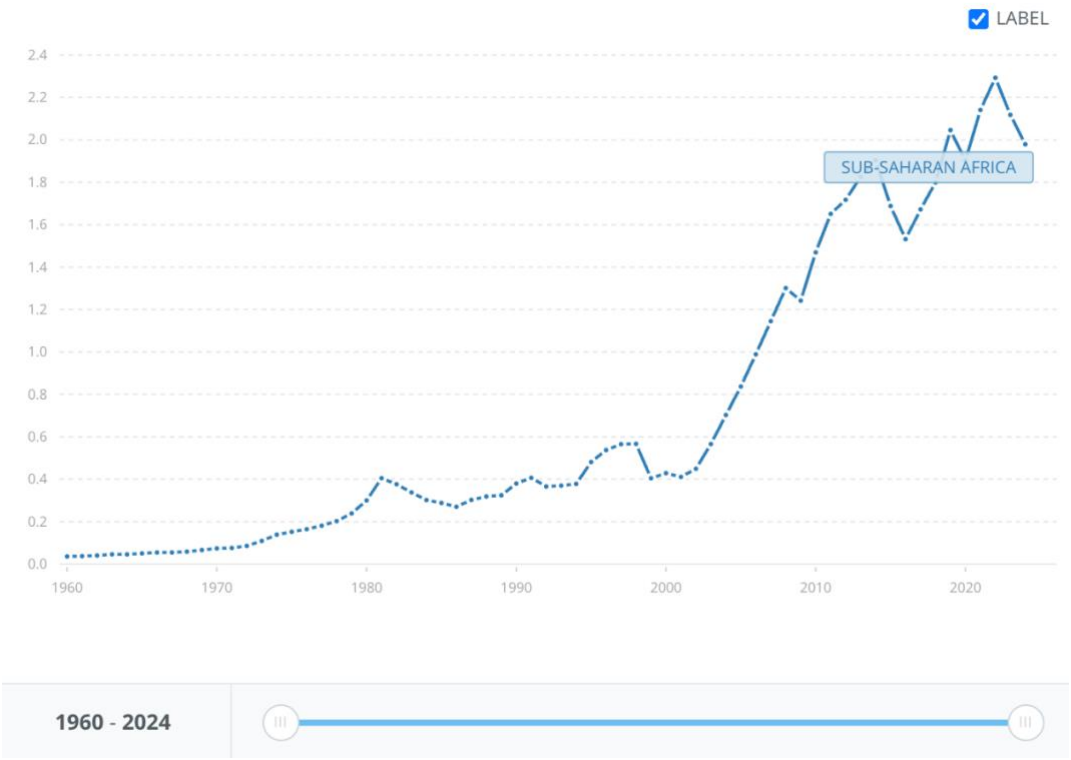


Figure 2: GDP (current US$) - Sub-Saharan Africa. Source World Bank (2026) [4].

From Figure 2 we can see how Sub-Saharian Africa's GDP has increased since 2000, going from 404.65 Billion to 1.98 Trillion in 2024.

However, the growth is characterised by instability and heterogeneity, due to the lack of a corresponding process of structural transformation able to modify the economy's composition and employment. Not all Sub-Saharan's countries faced the same economic progress, literature agrees that doesn't exist unique African development trajectory, but a multitude of national path influenced by different restrictions and heterogeneous geopolitical context (African Development Bank Group, 2025). Another crucial factor is

[4] (World Bank)

the distribution of natural resources, since, although the region is becoming increasingly integrated in the global supply chain thanks to the abundance of such resources, these are located in peripherical areas with a poor infrastructure system.

A key element that plays a crucial geopolitical role is the dependence on commodities. Several Sub-Saharan's countries base their economies on the export of oil, gas, minerals, and other commodities that expose them to the fluctuation of international prices, which cause vulnerability. On one hand the region benefits on raw material's price rise, engaging expansionary polices, but on the other hand when prices fall, the negative effects rapidly affect the public finance and polices. Remaining heavily reliant on the extraction of primary resources tends to hinder the development of more diversified and complex production bases, becoming not only a macroeconomic challenge, but also a restriction for new economic systems that are not able to generate wide and systemic demand of local productive infrastructure.

The low level of industrialization has a huge impact on the difficult for Sub-Saharan's countries of creating a sustainable and structural growth. World Bank research demonstrates that even in presence of participation in global values chains and manufacturing sector rise, the region's industrial base is fragile and not very diversified, concentrated on low-tech activities or industries not linked to the economy at large. In several countries manufacturing didn't lead to a wide transformation, able to influence the economic employment and landscape. The consequence is very limited local productivity, with limited production of intermediate goods, components and advanced services. These countries in fact participate to global value chain, but in subordinate position with low value added and limited opportunities for learning and upskilling. This perspective confirms the idea that a weak industrial base generates a weak economic system, because a poorly structured production system reduce the ability of sustaining complex infrastructure investments that are sustainable over time (David, Leibbrandt, Ranchhod, & Yasser, 2025).

Sub-Saharan economy, according to International Monetary Fund, is one of the regions with the highest rate of informal economy5 in the world, with levels that deeply impact on production and employment. This element results in the challenges for the State of collecting income tax, restricting the capacity for planning and public investments because development polices need official numbers/statistics on which base analysis. Informal economy also obstructs the access to formal financing, because the activities which influence are not able to provide balances, regular contracts or collateral accepted by the banking system (Medina, Jonelis , & Cangul , 2017). This aspect is also influenced by the fact that several African borders has been inherited by the decolonialisation epoch, where element such us consolidated trade and safety has not been taken into account. The result of this process led to have, nowadays, border areas as spaced for trade, but also zones of smuggling, armed mobility and competition among central authorities, local actors, and transnational groups. Therefore, borders become an element that can strengthen or weaken the state, because is the vehicle that can control what or who can move, who can trade and govern. To exercise sovereignty over the territory a State must monitor its borders and so its goods, weapons, and people flow, becoming a lever of governance and not just a geographical boundary.

This topic is particularly vulnerable when the borders is too large and far removed from the political centre, here the State shows its limits, with a sovereignty which remains de jure, but not de facto.

An example of this context is the border between south's Ethiopia and north's Kenya, where the large and sparsely populated border areas facilitate informal goods and people flows. In the areas of Moyale and Turkana, in periods of drought and when demographic pressures are intensifying competition for resources, the conflicts between local groups become cross-borders. Local communities don't follow national State logic,

[5] The informal economy refers to all economic activities by workers and economic units that are – in law or in practice – not covered or insufficiently covered by formal arrangements. It thrives mostly in a context of high unemployment, underemployment, poverty, gender inequality and precarious work. The situation is aggravated in conflict-affected and fragile situations where there is no other alternative than operating in the informal economy for securing livelihoods. In PROSPECTS' areas of interventions, the effects of refugee inflows are largely concentrated in the informal economy (International Labour Organization, s.d.).

but the clan culture based on the seasonal use of the territory. Therefore, these areas become perfect context for smuggling and informal transactions. (Zoppi, 2014)

On the other side Sub-Sharian Africa is, in the sight of several Countries and emerging actors, a space of growing interest. The territory hosts large deposit of natural resources with a growing market and a strategic position on routes between the Atlantic, the Mediterranean, the Red Sea, and the Indian Ocean. This enhances the interests of countries such as Cina, USA, European Union, India, Russia and so on, to invest in the region and become geopolitically relevant.
These countries are not doing business with Sub-Saharian Africa in general, instead only through strategic gateways, such us ports or resources-rich countries. Therefore, the region's geopolitics is selective to few countries, which form closer relationships with their investors, while other countries remain raw material supplier.

In order to protect the economic sovereignty and national interests, several countries limit the access to specific sectors, especially the sensible ones, such us energy, defence, and media. Here the investor can operate only through special licences, joint venture or other specific business methods. Limited doesn't means the investment is not prohibited, but that often needs to be approved by a public authority. Even with the approval, foreign operators may face more complex requirements regarding several aspects, such us registration, licensing, minimum capital requirements, reporting, and tax compliance. Additionally, it may be required the employment of local workforce and the transfer of technology to local authorities.
These policies' aim is preventing the investment from remaining detached from the national domestic economic landscape and consequently that doesn't contribute to the country's social and economic development.

These structural features have important implications for the development of the energy sector, contributing to the weakness of centralized energy systems and creates significant barriers to the expansion of traditional grid-based infrastructures.

2.2 Energy poverty and access challenges

Literature and international agencies reports show how the region has strong gaps between urban and rural areas, with grids concentrated in the most profitable centres (see Figure 3). In this panorama millions of people are excluded even if a theoretical connection exists. The problem is not producing energy but rather having reliable facilities that allow the transport at reasonable costs.

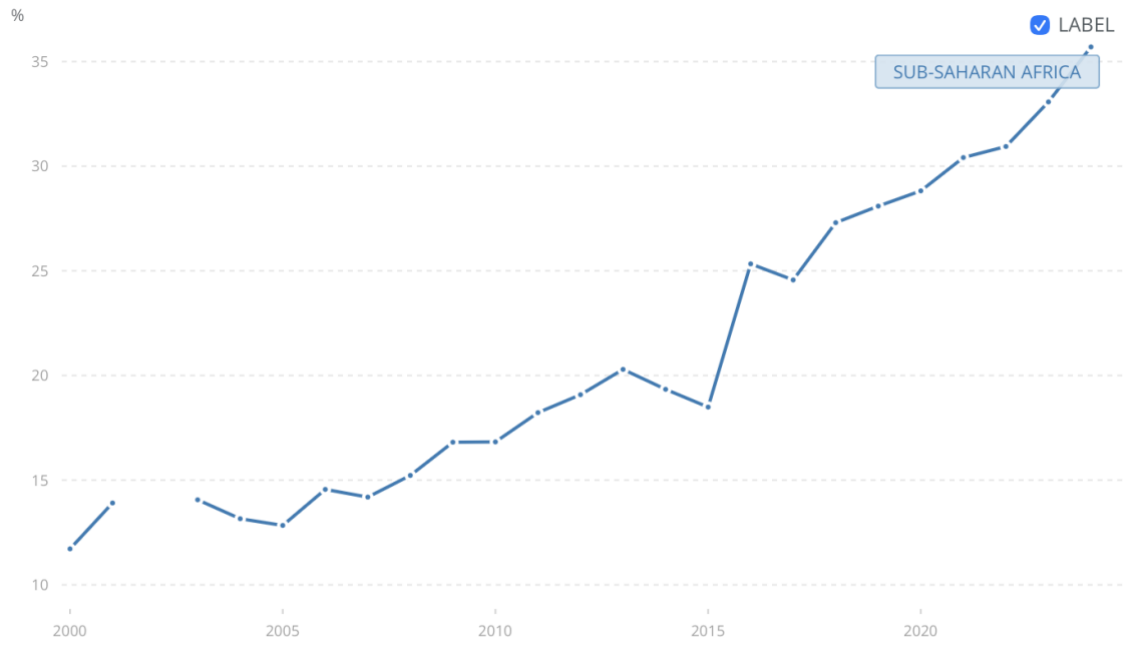


Figure 3: Access to Electricity, rural (% of rural population) - Sub Saharian Africa (World Bank, 2024).

In this context the concept of energy poverty[6] in Sub-Saharian Africa is becoming increasingly important. This concept is defined as a multidimensional condition that goes beyond the mere lack of an electricity connection. It addresses the constraints on the ability of individuals and companies to access modern and reliable energy services. The

[6] Energy poverty occurs when a household must reduce its energy consumption to a degree that negatively impacts the inhabitants' health and wellbeing. It is mainly driven by 3 underlying root causes: a high proportion of household expenditure spent on energy, low income, and low energy performance of buildings and appliances. (European Commission)

access to energy is a key trigger for the production development and the improvement of population's living conditions. (Sovacool, 2012)

Literature defines energy poverty as the inability to meet basic needs through adequate energy services, which involve several activities, such us lighting, food preservation, communication, study, the operation of healthcare facilities, and the use of production tools. The absence of these services, in Sub-Saharian Africa, adds complexity to the capability of attract human capital and develop local economical activities.

Therefore, energy become an enabler of economic growth, going beyond its infrastructural dimension, facilitating the integration of community in the national and international production system. Without a reliable energy access, numerous economic activities remain bound to low-mechanization practices that restrict the capacity to process local resources, resulting in severely depressed productivity levels. These factors impact the local business ecosystem, where small firms, traditionally a cornerstone of Sub-Saharan economies, confront numerous barriers resulting from inadequate energy supplies. Firms are compelled to rely on alternative energy solutions, frequently more costly and less efficient, thereby further constraining their economic competitiveness. (Bazilian, et al., Energy access scenarios to 2030 for the power sector in sub-Saharan Africa, 2012)

Furthermore, energy poverty carries deep repercussions for the social dimension as well. Education is negatively affected by the absence of modern energy services, given the constraints on studying at night and on accessing technological learning tools. Equally, the Healthcare facilities face obstacles in the operation of medical equipment, the preservation of pharmaceuticals, and the administration of essential services, due to the lack of energy supply.

Against this backdrop the energy issue is inextricably linked to the dynamics of human development and to the capacity of governments to provide adequate public services.

The peculiar infrastructures' location distribution reflects the deep territorial inequalities, which characterize Sub-Saharian Africa energy access and public investments. Main urban centres serve as the primary hubs for the development of centralized energy systems, driven by a higher density of demand and greater purchasing power. These factors render investments in grid expansion economically viable.

Conversely, rural areas either remain excluded or are limited to rudimentary and poorly integrated electrical infrastructure. (World Bank, 2025)

For the grid expansion high initial investments are required in infrastructures booth of transmission and distribution, investments whose economic rationale runs counter to the sustainability dictated by the distinctive features of rural areas. The expected financial returns undermine the interest of public and private operators in investing in traditional infrastructure development.
Urban areas more easily attract capital and productive activities participating in a cumulative process of growth, which increase the gap with marginal areas, reinforcing so the existing territorial imbalances.

As previously mentioned, a key issue in Sub-Saharian Africa's energy system is the quality and reliability of the electricity access. The actual system is not able to guarantee a stable and continue energy service, the instability of the grid voltage and the limited power production reduce the efficiency of the access. Even if in the last years the number of connections has increased the problem remains unsolved, leaving the families and firms to face blackout and a resources availability that impact on production and life conditions. The factors that impact on the reliability of the system are both technical and economical, because of the high levels of energy dispersion, due to the obsolete production plants and the vulnerability to climate, economical, and political shocks. In this context of overburdened grids, even relatively small increases in demand can generate widespread instability. Firms are forced to equid themselves with autonomous generator, batteries or backup system to ensure business continuity, impacting on the operational costs and production efficiency, which influence firm's competitiveness. (World Bank, 2025)

In this context, a vicious cycle is triggered, perpetuating conditions of economic underdevelopment and territorial marginalization over time. In several countries of Sub-Saharian Africa, energy is not yet able to satisfy the large-scale industrial transformation processes, but as mentioned, is perceived as a structural constraint for economic growth and ability to attract investments.

In these conditions numerous economical activities remain in sector with low added value, which require low level of mechanisation and technological innovation's capability. Rural areas especially, remain trapped in an infrastructural lock-in[7], which impact on the opportunity of building more articulated local markets and value chains. (International Energy Agency (IEA), 2022)

The results of this scenario are is an industrial and commercial energy demand that doesn't attract investment for more complex infrastructures. Deman is often fragmented and primarily domestic, reducing the bankability of project and the risk perception of public and private investors. (Bazilian, et al., Energy access scenarios to 2030 for the power sector in sub-Saharan Africa, 2012)

Key concept is that connection is not sufficient to produce development if competences, capital, services and entrepreneurial ability do not support it. Electricity doesn't automatically produce development but enables the economy impacting on structural element when interact with those elements. For this reason, the energy poverty can be interpretated as a multidimensional problem, where on one side firms need an adequate energy infrastructure to generate a stable demand, and on the other side the investors are waiting a stable demand to invest in energy grid development.

Therefore, energy access enables to analyse more flexible and decentralised solutions, which are not only technological grid alternatives, but mainly the trigger for interrupting the vicious cycle. In this perspective the values is given by the ability to activate efficient uses of energy, generating local competences and building clusters able to sustain the development in the long-term.

The highlighted critical factors show how the energy problem of Sub-Saharian Africa is not just technical but depends on the institutional and organizational structure that must

[7] Infrastructure lock-in describes a situation where the initial design and implementation of an infrastructure system creates path dependencies, making it difficult and costly to switch to more sustainable alternatives. This inflexibility can hinder the adoption of innovative technologies and practices that could reduce environmental impact and promote long-term ecological health. It represents a significant challenge in transitioning to a sustainable future, as it perpetuates reliance on outdated and often environmentally damaging systems. Addressing infrastructure lock-in requires proactive planning, flexible design, and a willingness to invest in transformative solutions. (Sustainability Directory)

be implemented to finance and develop the system. The administration restrictions and regulatory uncertainty are nowadays insufficient to sustain the required process in the long-term. Financial institutions, public actors and private investors need high levels of coordination to build a sustainable energetic system and its infrastructures. Therefore, energy planning tends to focus on short-term interventions and in strategic areas where the investment is able to produce profit for booth the region, on social and industrial dimensions, and for the investors, in terms of revenues. (Sovacool, 2012)
In different contexts, energy firms perform in high level of debt and a strong reliance on international financing, with a low capability of autonomously sustain expansion and modernisation of energy grid.

From this perspective, analyzing Sub-Saharan Africa's energy issues requires considering not only the economic and territorial limits of energy access, but also the ways in which infrastructure, institutions, and governance interact to determine the sustainability and evolution of regional energy systems.

2.3 Infrastructure and governance issues

The operation of centralised energy system is characterised by a high level of complexity, due the fact that they don't depend only on the technical ability of producing energy, but also by the presence of economical and institutional factors that impact on their long-term development. Electric grids require a high level of coordination between different element: production, transmission, distribution, regional planning and demand management. Maintain the balance among these elements pass through regular investments, maintenance and coherent decisional processes.

The industrialisation period and the consolidation of the modern State have been critical factor in the development of large energy grids, which played a key role in the integration among internal markets and the concentration of production activities. However, in several Sub-Saharian Africa's countries, characterised by significant territorial discontinuities, these systems result incomplete. As explained in the previous paragraph, electric grids present a fragmented configuration, clustered around main urban, industrial and administrative centres, not providing an homogeneous distribution throughout the region (see Figure 4).

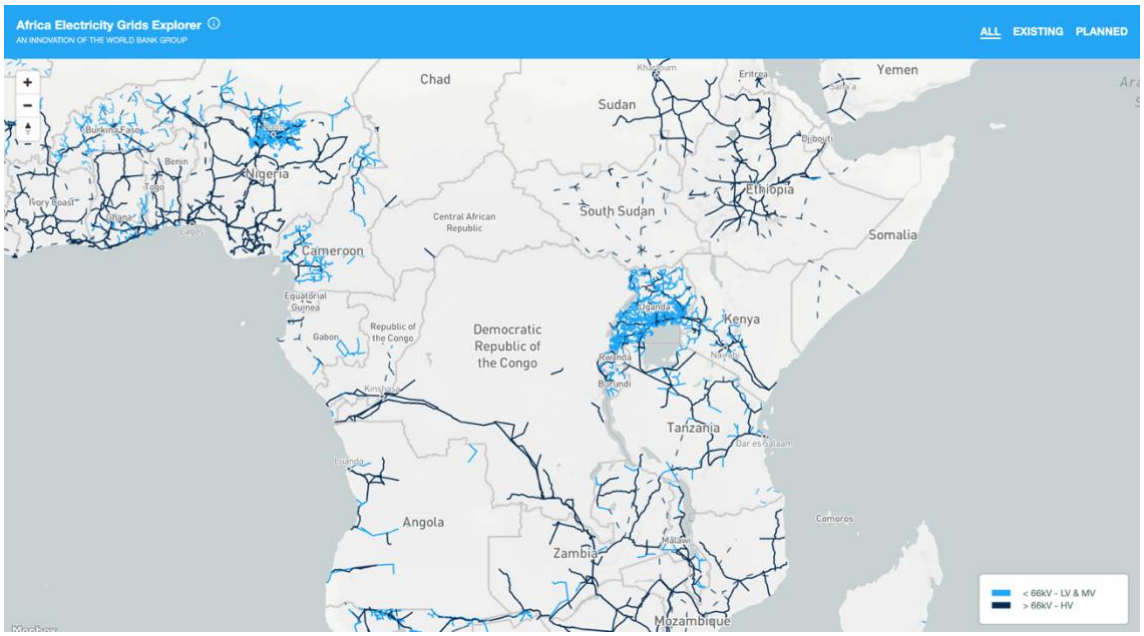


Figure 4: Africa - Electricity Transmission and Distribution Grid Map[8].

The investment in the development of new infrastructure present long-term revenues that don't attract investor's interests. To become more attractive, these systems need integrated markets where the consumption is predictable, with a stable demand the energy operators can rely on a financial continuity. Utilities' ability to produce stable revenues facilitate the sustain of grid's expansion and modernisation processes.

Furthermore, consideration must be given to the complex element of institutional managing and coordination of the energy sector. Centralised grid infrastructure requires decisional continuity and long-term planification, because the energy cycle's investments frequently span decades. The high political instability and frequent regulatory reforms impact on the dependence on international financing, where the short-term logic takes the lead. Ministries, regulatory bodies, public utilities, private investors, multilateral development banks, and international organizations frequently operate with divergent goals. This complicates the development of cohesive infrastructure strategies, thereby elevating the risk of inefficiencies. Against this backdrop, the capacity for coordination emerges as an element as critical as the availability of financial capital. (Geels F. W., 2004)

[8] (World Bank Group, s.d.)

2.4 The rise of off-grid solutions

As previously mentioned, a critical constraint is represented by the ability of institutional and financial actors of coordinate among themselves, but also by the availability of capitals. In response to these problems, which have a strong impact on the expansion of the traditional centralised grid, the off-grid solutions rise as technological alternatives.

The diffusion of these solutions can be interpreted in light of Rodriguez-Clare contribution, whereby in the presence of market and coordination failures, spontaneous organisational structures, like clusters, arise in order to reduce the risks and to facilitate the collective action across multiple stakeholders, which the market is unable to attract. However, the off-grid as manifestation of cluster logic, collides with the critical elements of the geographical proximity that we addressed in the previous Chapter, a critical concept for the enabling of tacit knowledge diffusion and spillovers generation. Off-grid solutions, by their nature, born to respond to a spatially dispersed demand.

This distance is reconciled by distinguishing between the dimension where concentration takes place from that where dispersion occurs. The cluster remain a spatially concentrated ecosystem of firms, investors, and institutions, which generate innovation and coordinate the productive activity. Instead, the off-grid is the technological and business model through which the cluster output reaches the geographically dispersed demand. The Nairoby's cluster, which will be analysed in the next Chapter thus emerges as a concentrated hub of production and innovation, functional to serving a structurally decentralized demand.

This point of view is supported by Alstone, Gershenson and Kammen (2015), who propose an analytical framework that doesn't identify the electric grid as a unique generating and transmission infrastructure, but rather as a continuum of local and autonomous technological solutions (often photovoltaic). The framework considers the energetic solutions as a set of centralised grid, autonomous mini-grid, and standalone systems. Alston, Ghershenson and Kammen's work confirm the the distinction made above between a concentrated level of innovation and a dispersed level of service delivery. (Alstone, Gershenson, & Kammen, 2015)

Technologically and economically, the widespread adoption of off-grid solutions in Sub-Saharan Africa was facilitated by sharp cost reductions in photovoltaic and storage technologies, creating economic feasibility for small-scale applications, spanning standalone Solar Home Systems (SHS) to community-based mini-grids (International Renewable Energy Agency, 2016). A key enabler was the synergy with expanding mobile money ecosystems, facilitating the roll-out of pay-as-you-go (PAYG) schemes: consumers repay hardware costs via platform-mediated instalments, thus unlocking the liquidity and credit constraints that, as argued in Section 3.1, prevalent throughout the region's informal sector. (GOGLA, 2024).

The core of this financial architecture is M-Pesa[9], the Kenyan mobile money infrastructure, which development had a strong economic impact, drastically reducing transaction costs and enabling the possibility for families to build geographically dispersed support networks rather than just local ones, developing the families' ability of sharing risks (see Figure 5 below). Before, if a family in a rural village suffers a financial shock, they could only ask for support from close relatives and friends, due to the high costs and slow processing times of money transfers. (Jack & Suri, 2014)

[9] M-PESA is a peer-to-peer mobile money transfer service launched in 2007 on the mobile network of Safaricom, a Vodafone affiliate, to enable microfinance institutions to easily send and receive money from borrowers. (M-Pesa, 2023)

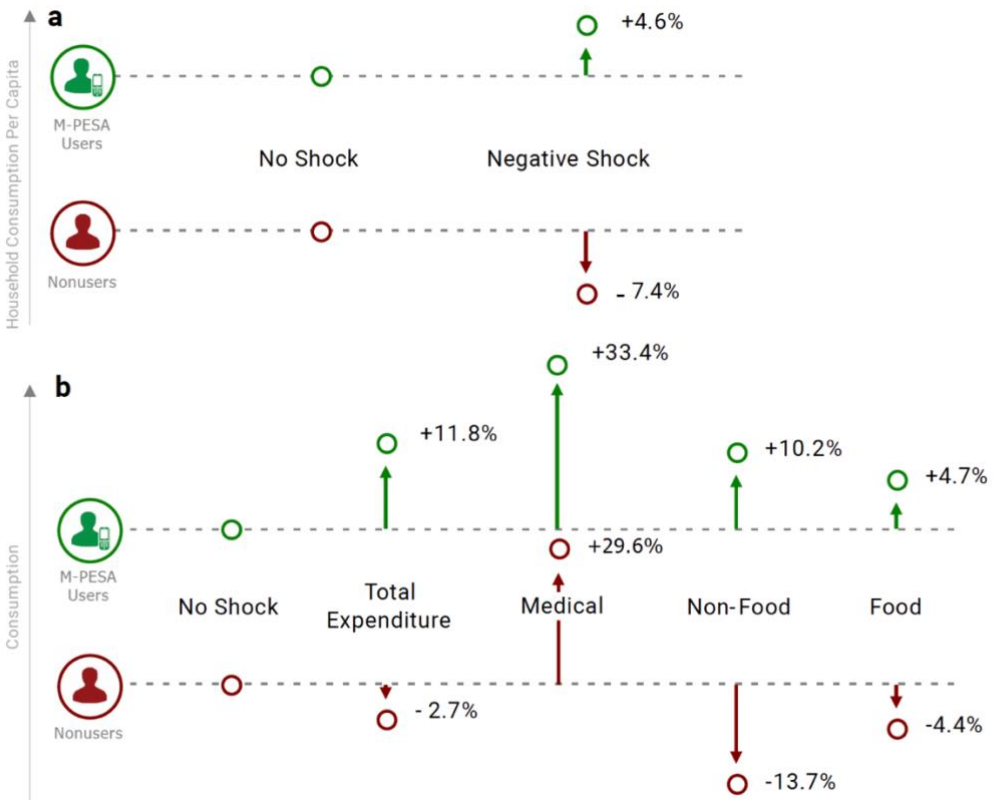


Figure 5: Resilience of M-PESA users and nonusers to economic shocks. Panel a is based on data from Jack and Suri (2014); panel b is based on data from Suri et al. (2012)[10]

This financial infrastructure is a key element for understanding why Kenya has served as a testing ground for the introduction of the PAYG model in the off-grid energy market, allowing consumers to pay for the systems in instalments through digital platforms and thereby overcoming the barrier of access to formal credit

The outcome of this model has captured the interest of a heterogeneous group of actors, such us tech enterprises, financial institutions, venture capitalist, and Development institutions. Their ability to serve a dispersed and fragmented end-user base while maintaining spatial proximity is what anchors this dynamic to the cluster model, distinguishing it from uncoordinated and fragmented technological diffusion.

It is against this backdrop that the case of the Nairobi off-grid cluster is situated. Selected as a case study, it represents one of the continent's most pivotal ecosystems for

[10] (Suri, et al., 2023)

decentralized energy innovation, thereby providing a prime setting to empirically observe the industrial and social spillover dynamics discussed in Chapter II.

Chapter III The Nairobi Off-grid Cluster

3.1 Kenya Energy sector

Kenya Energy system stands out for its significance in Sub-Saharan Africa, due to the advanced institutional reform process compared to the region average, the structural imbalances that characterize the development and the energy mix oriented to renewable energies. To analyse the off-grid ecosystem developed in Nairobi as answer to the structural limitations of the grid system, is critical understand the country's historical and technological evolution.

Till the 1990s the Kenyan's energetic system was organised on a unique state utility monopoly, vertically integrated, responsible of entire energy supply chain, from the generation to the distribution. This system was characterised by managerial inefficiency and high commercial and technical losses, emphasised by the limited investment capacity. Karekezi and Kimani (2002) highlights, in their analysis of African electric system and the reforms to which it has been subjected, how the low-income segments of population have been disproportionately disadvantaged, both because of the accessibility and the costs.

From the 1990s, thanks to the privatization program promoted by the multilateral financial institution, Kenya has been through a series of structural reforms, which have led to the unbuilding of the previous state utility monopoly in three separated company:

- Kenya Electricity Generating Company (KenGen)[11]: Responsible for the generation.
- Kenya Electricity Transmission Company (KETRACO)[12]: Responsible for high-voltage transmission.
- Kenya Power and Lighting Company (KPLC)[13]: responsible for distribution and retail supply.

  KPLC, which previously was the only monopolist company, has been partially privatised by going public.

[11] https://www.kengen.co.ke/
[12] https://www.ketraco.co.ke/
[13] https://kplc.co.ke/

Simultaneously, was established Energy and Petroleum Regulatory Authority (EPRA)[14], whose purpose is monitoring the sector competition, having strong power in the definition of tariffs and in the licensing.

This new environment has attracted the actions of Independent Power Producers (IPP), whose thanks to long-term Power Purchase Agreement (PPA) with KenGen or KPLC, have entered the market and progressively icreased the installed generation capacity, especially in the renewable energy segment.

Despite the deep reform, which transformed the sector through an advanced and prolonged process across the continent, the structural criticalities have not been fully addressed. In this context the financial sustainability of the KPLC continue to constitute a risk, which can have high and direct impact on the system ability to finance the grid expansion toward rural areas. (Karekezi & Kimani, 2002)

The current regulatory framework is regulated by the Energy Act 2019[15], which replaced previous legislations, which enhanced EPRA's regulatory mandate and established provisions aimed at promoting renewable energy sources and distributed mini-grid solutions. The Ministry of Energy, in collaboration with KenGen and KETRACO, periodically develops the Least Cost Power Development Plan, a document that guides the sector's long-term planning by establishing criteria for cost minimization and security of supply in order to define the development of power generation capacity and the transmission network. Particularly relevant, from an institutional point of view, is the administrative decentralisation process initiated by the Kenyan 2010 Constitution[16], which transferred responsibilities for strategic planning in the energy sector from the central government to the 47 county governments. (Volkert & Klagge, 2022)

While this process is meant to tailor planning more closely to local needs, in practice it has encountered several hurdles, including the enduring concentration of technical and financial capacity at the national level and the lack of adequate local administrative capacity, further compounded by regulatory fragmentation that has created overlapping jurisdictions between central and local authorities.

[14] https://www.epra.go.ke/
[15] (Republic of Kenya, 2019)
[16] (Republic of Kenya, 2010)

From this panorama we can see how the intention of the legislator of enabling the expansion of distributed energetic solution has not yet fully matured the institutional conditions required to support it and enable systematic development.
This gap created market opportunities for private actors, with the Nairobi off-grid cluster serving as the preeminent example.

Kenya distinguishes itself across Sub-Saharan Africa through an energy mix predominantly driven by renewables, earning recognition as a compelling case study on the global stage.
Kenya possesses among the highest geothermal endowments in Africa, largely concentrated in the Olkaria area[17] within the Rift Valley, a geological feature toward which the country has directed substantial public and private capital. Kiplagat, Wang, and Li (2011) point out that alongside this geothermal endowment lies substantial geographical potential for hydro, wind, and solar energy. However, they emphasize that their exploitation remained limited, constrained by technical capacity and the aforementioned factors. In the years following this study, renewable power generation capacity underwent substantial expansion, most notably in the wind energy sector through the Lake Turkana Wind Power project[18] (Africa's largest wind farm, sited in northern Marsabit County) marking a critical milestone in the diversification of Kenya's power mix. Simultaneously, utility-scale solar PV capacity expanded considerably, driven by plunging technology costs worldwide. (Mainali & Silveira, 2011)

This structure mitigates Kenya's vulnerability to international oil price shocks, placing the country at a comparative advantage over regional counterparts that rely heavily on imported fossil fuels. Nonetheless, it fails to remedy the core challenge of rural electrification, which stems, as discussed in the preceding Chapter, from the stark divergence between concentrated industrial and commercial load in urban hubs and dispersed consumption across rural localities. Persistent structural bottlenecks, despite sweeping reform efforts, continue to undermine overall system performance. Grid transmission and distribution losses, though trending downward, exceed benchmarks

[17] https://www.kengen.co.ke/our-business/energy-generation/geothermal/
[18] https://ltwp.co.ke/

for upper-middle-income economies, while KPLC's financial viability remains undermined by revenues that do not systematically recover operational and capital costs, despite repeated corporate restructuring programs. Crucially, these constraints impair the state utility's ability to independently finance grid extensions into remote, low-income communities with low purchasing power.

Stemming directly from this structural constraint within the centralized grid, Kenya's off-grid solar market began its rapid ascent in the 2000s. In comparative research on solar market dynamics across Kenya and Tanzania, Ondraczek (2013) illustrates how Kenya emerged as a global frontrunner in off-grid solar adoption, achieving installed capacities and solar home system deployment figures that vastly outstripped Tanzania's, despite comparable agro-climatic conditions. Crucial catalysts for this development included widespread product availability and decreasing retail costs, which together bolstered end-user awareness. Ultimately, these factors underpinned the emergence in Nairobi of a dedicated entrepreneurial and financial hub centered on decentralized renewable energy solutions.

Today, Kenya's energy system is characterized, on the one hand, by a centralized grid underpinned by a well-balanced energy mix, whose expansion remains constrained by financial and geographic factors; on the other hand, by an off-grid market that has reached maturity and progressively attracted a wide range of actors, including investors, enterprises, international organizations, and skilled labor, laying the groundwork for the emergence of an energy cluster. (Ondraczek, 2013)

3.2 The off-grid solar system and the PAYG cycle in practice

Before analysing the ecosystem of actors that make up the Nairobi cluster, it is useful to clarify exactly what the product is around which this ecosystem has developed, and how—from both a technical and commercial standpoint, the cycle works that brings a solar system from the factory to the home of a rural Kenyan customer. This operational introduction does not introduce new theoretical elements but provides the concrete framework that the following Sections, dedicated to the structure of the stakeholders and spillover effects, take for granted.

From a technical standpoint, the products that make up the Kenyan off-grid market do not constitute a homogeneous category but are distributed across multiple levels, distinguished by size and service capacity, consistent with the framework proposed by Alstone, Gershenson, and Kammen, as discussed in Section 2.4. At the lower end of the spectrum are pico-solar products: small lanterns or solar kits equipped with a low-power photovoltaic panel, a rechargeable battery, and a limited number of LED lights (see Figure 6 (a)).

Solar Home Systems (SHS) (see Figure 6 (b)) proper can be placed one step higher: a panel with greater capacity, a battery, traditionally lead-acid, but increasingly lithium-ion, and a control unit connected to multiple light fixtures, USB charging ports for cell phones, and, in higher-end kits, additional devices such as radios or small televisions. Above this segment are C&I solutions, designed for commercial and industrial users (see Figure 6 (c)), and mini-grids (see Figure 6 (d)), which serve multiple users through a shared local distribution network, the same three-part classification already used in Figure 8 to break down the sector's formal composition. (International Renewable Energy Agency, 2016)

From the customer's perspective, the process of purchasing a SHS follows a sequence that has now become standard in the Kenyan market. The customer pays an initial deposit, typically a small fraction of the system's total price, sufficient to cover distribution and installation costs; the system is then installed at the customer's home by a representative of the selling company, and the remaining balance is paid off through periodic payments (daily, weekly, or monthly) made via the mobile money platform discussed in Section 2.4, over a period typically ranging from one to three years. At the end of the payment plan, ownership of the system is transferred in full to the customer, who from that point on may use it without any further contractual obligations. (GOGLA, 2024)

It is precisely during this intermediate phase, the instalment payment period, that the technical mechanism enabling the remote control discussed in Section 3.4 in connection with Figure 6 comes into play. The control unit integrated into the system includes a GSM communication module, equipped with its own SIM card, which allows the

company's platform to remotely verify the status of the customer's payments and to transmit an activation or deactivation signal to the device, without the need for any physical intervention on the system itself. This mechanism is a distinctive feature of the PAYG model compared to traditional sales: ownership of the good is acquired gradually, not at the time of purchase but upon completion of the payment plan, and the relationship between the company and the customer remains mediated, for the entire duration of the contract, by a technical device capable of monitoring and penalizing the customer's payment behaviour in real time.

Finally, in terms of the physical supply chain, that will be discussed in detail in Section 3.4, The main components, particularly photovoltaic panels and electronic components, are imported, primarily from the Asian market, and then assembled and configured into kits ready for sale at local facilities. From there, the product reaches the end customer through a network of local sales agents, who are responsible for both door-to-door sales and initial installation at the customer's home.



Figure 6: (a) A pico-solar lantern[19], (b) A residential Solar Home System (SHS) starter kit[20], (c) A commercial & industrial (C&I) rooftop solar installation[21], d) A solar mini-grid serving a rural community[22]

3.3 The Nairobi off-grid ecosystem

In order to understand why the cluster is concentrated and developed in the Nairobi metropolitan area, is important to start from the element that the city is historically recognised, in the African technological innovation' literature, as a one of the continent's centres of excellence for digital entrepreneurship. Indeed, the term "Silicon Savannah" has now become firmly established in academic discourse. (Graham & Mann, 2017)

[19] Source: Sun King, https://sunking.com/product/pico-plus)
[20] Source: PowerPoint Systems EA, https://powerpointsystemsltd.com/products/starter-home-hybrid-solar-kit,
[21] Source: Orb Energy, https://ke.orbenergy.com/commercial-industrial-rooftop-solar/
[22] Source: RMI, https://rmi.org/rmi-insights/sharing-the-power/

Understanding the origins of Nairobi's technology ecosystem begins with an analysis of the business process outsourcing and software development sectors. Starting from this point helps us understand why human and venture capital in the digital sphere have attracted a variety of players, from entrepreneurs to investors, leading to the creation of relationships that have subsequently shifted the focus to different sectors, including decentralized energy. This element is critical, because confirm on the constitutive pillars of a cluster, which we addressed in the Chapter I: the existence of a geographical area with a dense network of relationship, active institutions and specialized human capital, which enable also the labour market pooling for sectors different from the original ecosystem.

In this context, the leading companies that have driven the pay-as-you-go model in East Africa's off-grid solar market have chosen to establish their operational and strategic headquarters in Nairobi. M-KOPA[23], one of the sector's pioneering companies, was founded in Nairobi by a group of managers with direct experience in the digital payments sector. This connection also allows for a quicker understanding of the causal relationship, discussed in Section 2.4, between mobile money infrastructure and the emergence of the PAYG business model applied to energy. Alongside M-KOPA, Nairobi is home to the headquarters of Sun King (formerly Greenlight Planet[24]), one of the world's leading providers of residential solar systems, as well as the regional operations of other major players in the sector, such as BBOXX[25] and Azuri[26]. The coexistence of these operators—who are, strictly speaking, competitors, within the same urban area precisely reflects the logic of "co-opetition" (competition and cooperation) identified by Porter as a defining characteristic of industrial clusters: companies compete for market share and access to capital, but they share often informally human capital, suppliers, and customers, and in some cases even logistical infrastructure.

Around this ecosystem of technology companies, a network of supporting actors has gradually developed. This multi-actor structure is, in fact, already anticipated by Porter's own definition of cluster discussed in Section 1.1, which explicitly includes among the

[23] https://www.m-kopa.com/
[24] https://ke.sunking.com/?ats=1
[25] https://www.bboxx.com/
[26] https://www.azuri-group.com/

constitutive elements of a cluster "governmental and other institutions... universities, standard-setting agencies, think tanks, vocational training providers, and trade associations" alongside firms and specialized suppliers (Porter, Clusters and the New Economics of Competition, 1998). This structural feature is independently confirmed by a distinct strand of literature focused on technological innovation processes: Ogeya and Lambe (2025), applying the Technology Innovation Systems (TIS) framework to the analysis of mini-grid development in Kenya, show that the diffusion of decentralized energy solutions is necessarily a multi-stakeholder process, involving firms, networks of relationships, end users, and government agencies, all interacting within a political and economic context that shapes their development trajectories. Although the TIS framework originates from a different theoretical tradition than Cluster Theory, its findings converge empirically with Porter's taxonomy, reinforcing rather than displacing the interpretive framework adopted throughout this thesis.

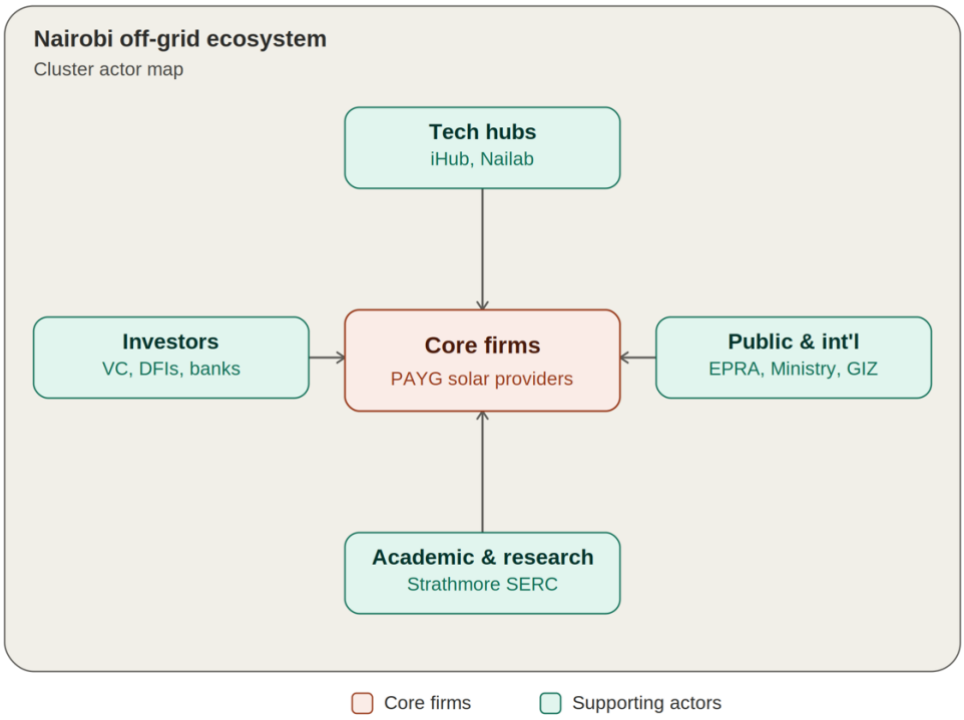


Figure 7: Actor map of the Nairobi off-grid ecosystem. Author's own elaboration

Applying this composite reading to the specific context of Nairobi, it is possible to identify at least four categories of actors that complement the technology companies already discussed (see Figure 7):

- First, a network of technology hubs, incubators, and business accelerators—which emerged and developed in the early 2000s as part of the broader growth of the Silicon Savannah ecosystem, including iHub[27], a recognized hub for Nairobi's digital entrepreneurial community, and Nailab[28], have gradually expanded their scope beyond pure software, offering shared workspaces, mentorship programs, and connections with investors even to startups in the energy sector. These spaces serve, in terms of the Cluster Theory discussed in Chapter I, as supporting institutions that facilitate collective learning and the circulation of tacit knowledge among entrepreneurs, thereby reducing search costs and barriers to entry for new entrants to the sector.
- Second, an ecosystem of investors has progressively focused its attention—and often its operational presence as well—on Nairobi as a preferred platform for accessing the off-grid market in East Africa: impact investing and venture capital funds specializing in energy access, development finance institutions, and, more recently, international banks involved in securitizing receivables generated by PAYG contracts. The physical concentration of these investors' local offices in Nairobi reduces the costs of due diligence and investment monitoring, further reinforcing the logic of geographic proximity discussed in Chapter I as an enabling condition for the flow of information and trust within the cluster.
- Third, a network of academic and applied research institutions contributes to the development of specialized human capital and the generation of technical knowledge and know-how that can be utilized by the sector. A notable example is the Strathmore University Energy Research Center (SERC), an applied research center established in 2012 at Strathmore University in Nairobi, which is involved, among other things, in the technical training provided under the Kenya Off-Grid Solar Access Project (KOSAP)[29], a program funded by the World Bank and implemented in collaboration with the Ministry of Energy, KPLC, and the Rural Electrification Agency. The presence of this type of institution replicates, within an energy context, the role played by technical universities in the traditional

[27] https://ihub.co.ke/
[28] https://www.nailab.org/
[29] https://www.iea.org/policies/17733-kenya-off-grid-solar-access-project

industrial clusters discussed in Chapter I: providing a base of specialized skills that continuously feeds the local labor market and supports technology transfer processes.

- Finally, a fourth group of actors consists of government agencies and international cooperation organizations, whose role, as discussed in the previous paragraph with regard to the process of administrative devolution, remains ambivalent: on the one hand, the Ministry of Energy, EPRA, and REREC intervene through planning tools and co-financed electrification programs; on the other hand, bilateral and multilateral cooperation agencies have operated in Nairobi as intermediaries between the public sector, private companies, and international financiers, helping to fill, at least partially, the institutional coordination gap discussed in Section 3.1.

Before proceeding with the analysis, it is necessary to address two discrepancies between the case described here and the theoretical framework presented in Chapter I. The first concerns the size of the firms involved: the classic definition of a cluster adopted in Section 1.1 refers primarily to small and medium-sized enterprises, whereas the core of the Nairobi ecosystem consists of multinational-scale firms, backed by substantial international venture capital. This requires some adjustment, because, as discussed in Section 1.3 with regard to clusters in developing countries, the literature acknowledges that, in contexts characterized by market failures and a local entrepreneurial fabric still in the process of formation, the cluster development initiative may be driven by a limited number of larger actors, often of international origin, rather than by a multitude of local SMEs, as in the classic Marshallian model. The Nairobo-ta cluster should therefore be understood as a variant in which the function of geographical proximity is fulfilled by a limited number of international operators around whom the network of local investors, institutions, and suppliers described above has subsequently coalesced.

The second discrepancy concerns the socio-territorial dimension of the cluster, which is central to Becattini's contribution cited in Section 1.1. Thus far, the description of Nairobi's ecosystem has focused on formal actors, such as firms, investors, and

institutions, and on the functional relationships among them, without explicitly addressing the component of informal community and shared identity that the theory identifies as a distinctive feature of the cluster as opposed to a mere concentration of unconnected firms. However, this component is not absent in the case of Nairobi. The literature of the technological ecosystem of the urban area documents how the sense of belonging to a community of innovators, fueled by shared use of spaces such as iHub and participation in events, competitions, and mentorship programs, constitutes a factor of cohesion recognized by the entrepreneurs themselves as crucial in building mutual legitimacy and creating networks of informal trust. It is precisely this informal relational infrastructure, inherited from the broader Silicon Savannah ecosystem, that has provided the off-grid energy sector with a pre-existing foundation of social capital, reducing the coordination costs that an emerging sector would otherwise have had to build from scratch.

3.4 Interconnections and spillover effects

This Section analyzes the nature of the interconnections among these actors and the resulting industrial and social spillover effects. It is within this dynamic context that the Cluster Theory discussed in Chapter I finds its most direct validation: it is not the mere spatial co-presence of firms and institutions that generates value for the region, but rather the density and quality of the relationships that develop within it, through Marshallian externality mechanisms, namely, the circulation of tacit knowledge, labor market pooling, and proximity to specialized suppliers, as previously discussed in the Section on the economics of clusters.

The interconnections among the actors in the Nairobi ecosystem take both formal and informal forms. On a formal level, companies such as M-KOPA, Sun King, and BBOXX maintain structured contractual relationships, such as equity agreements, debt instruments, and securitization transactions involving PAYG receivables, with the investors discussed in the previous paragraph, as well as applied research collaborations with institutions such as the Strathmore Energy Research Center, and partnerships with public agencies within the framework of co-financed programs such as the aforementioned Kenya Off-Grid Solar Access Project. On an informal level, however, a

network of relationships is developing that is equally significant for generating knowledge spillovers: the mobility of skilled personnel among formally competing firms, one of the channels for the transmission of tacit knowledge already discussed in Chapter I alongside informal interactions and imitation. In Nairobi, this mechanism manifests itself through the movement of managers and technicians between the sector's pioneering firms and the second-generation startups that are gradually emerging in its supply chain, often founded by former employees of the leading firms, who bring with them the technical, commercial, and relational skills they acquired at their previous employer.

From an industrial perspective, the most significant spillover effect involves the gradual consolidation of a local supply chain centered on the sector's leading companies. Bhamidipati and colleagues, in a study conducted in collaboration with the Strathmore Energy Research Center as part of the UNEP-DTU Partnership's TEMARIN[30] project, analyze in detail the mechanisms of local value capture generated by the solar photovoltaic industry in Kenya, documenting how a network of local suppliers providing assembly, distribution, installation, and after-sales service has gradually developed around the leading companies (see Figure 8). However, that local value capture remains concentrated in the lower-value-added stages of the supply chain (distribution, retail, and maintenance) while the more technologically sophisticated components, such as the production of photovoltaic panels and electronic components, are still largely imported, primarily from the Asian market. (Bhamidipati, et al., 2021)

[30] https://unepccc.org/new-approach-for-tech-transfer-and-diffusion/

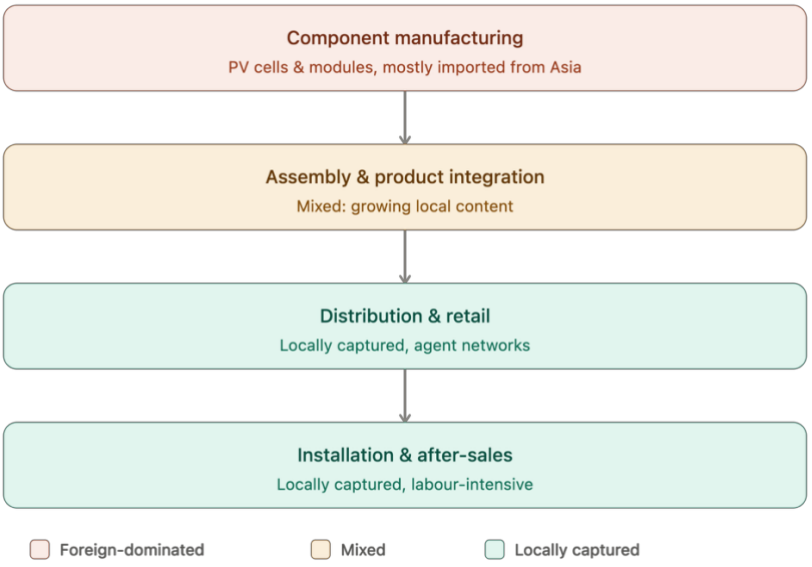


Figure 8: : Local value capture along the Kenyan solar PV value chain. Author's own elaboration, based on Bhamidipati et al. (2021)

This finding is of particular interest in light of the upgrading framework already introduced in Chapter I with regard to clusters in developing countries: the Nairobi ecosystem shows clear signs of functional upgrading, as local providers of distribution and technical support services have progressively expanded their scope of operations along the value chain, and of cross-sectoral upgrading, as the technical and digital skills developed in the off-grid energy sector are being repurposed in adjacent sectors, such as fintech. This phenomenon stems directly from the circular flow between payment data generated by PAYG contracts and the development of digital credit-scoring tools, further fuelling the Nairobi fintech ecosystem discussed in relation to M-Pesa in Section 2.4. However, there are no equally robust signs of product or process upgrading in the manufacturing sector itself, which remains concentrated outside the African continent. This represents a structural constraint on the cluster's full maturation in the Marshallian sense.

From a social perspective, the most widely documented spillover effect concerns the creation of direct and indirect jobs throughout the PAYG model's distribution chain. Unlike the production and research and development phases, which are concentrated in Nairobi, the sales and customer service phase necessarily requires a widespread

presence across the territory, through networks of sales agents operating in the rural areas served by solar systems. This configuration once again reflects the distinction between the concentration of innovation and the dispersion of demand already discussed in Section 3.4 of the previous Chapter but adds another layer: the creation of local jobs in outlying areas, generated by a command center concentrated in Nairobi. Quantitative estimates of the scale of this employment, however, vary significantly depending on the source and the methodology used. Much of the discrepancy between the figures reported in the literature reflects the fact that different studies cover technology segments that vary greatly in terms of their share of employment. In 2017-2018, the pico-solar and Solar Home Systems segment alone accounted for 78% of formal employment in Kenya's DRE[31] sector, compared with 18% in the C&I[32] sector and just 4% in mini-grids and solar pumps (see Figure 9). A report focused on a single segment yields much lower figures than a survey of the entire sector, a factor that calls for a cautious interpretation of the available data in this area.

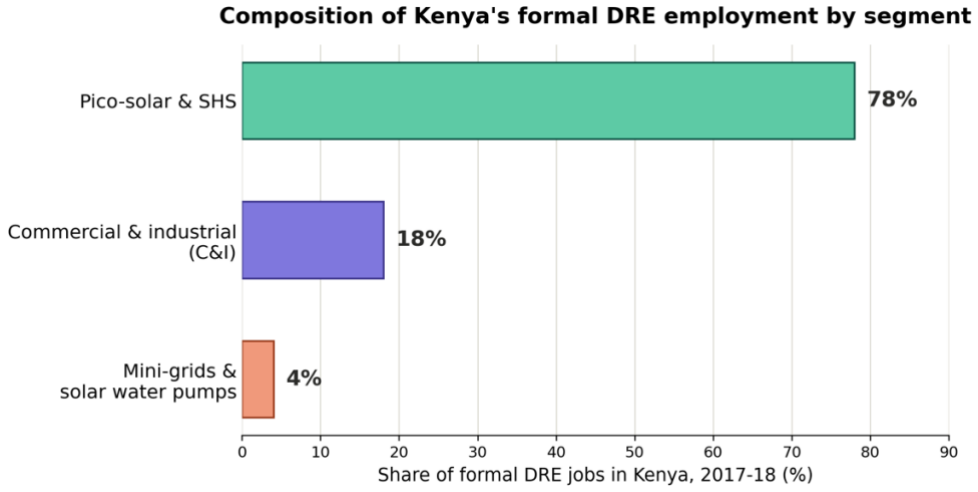


Figure 9: Composition of Kenya's formal DRE employment by segment, 2017-18. Source: Shirley et al. (2019)

It is precisely on this point that the most recent literature introduces a necessary element of caution to balance the interpretation presented thus far. Radley and Lehmann-Grube, in a systematic review of 125 studies published between 2001 and

[31] Distributed Renewable Energy
[32] Commercial and Industrial

2020 on the relationship between the expansion of off-grid solar power and economic development in the Global South, highlight that, although the majority of the studies analyzed (96 out of 125) report a positive influence on local economic development, this assessment is often based on a narrow conception of economic development, limited to increases in individual or business income, without verifying whether such gains are sustained over time or distributed equitably among the actors in the supply chain. The authors also highlight the need for a more critical analysis of the role of foreign companies in capturing the value generated, and of the unequal distribution of benefits among the various groups involved in the process. This observation ties directly into the finding, discussed above, regarding the concentration of local value capture in the stages of the Kenyan supply chain with the lowest value added.

3.5 Challenges and sustainability of the cluster

The preceding paragraphs have highlighted the two structural shortcomings of the Nairobi empirical case with respect to the theoretical framework presented in Chapter I: on the one hand, the nature of the cluster's entrepreneurial core, which is driven by a small number of multinational-scale firms rather than by the widespread network of local SMEs envisaged by the classical Marshallian model; on the other hand, the concentration of local value capture in the lower-value-added stages of the supply chain, with the most technologically sophisticated components continuing to be imported. This Section systematizes these tensions, along with others mentioned only briefly thus far, into a comprehensive analysis of the challenges affecting the cluster's long-term sustainability, organized across four dimensions, technical, financial-social, macroeconomic, and institutional, before concluding the Chapter and addressing, in Chapter IV, a more explicit comparison with the initial theoretical framework.

A key concern relates to the technical sustainability of the business model that has driven the cluster's growth. Harrington and Wambugu, in their specific analysis of the technical support and repair ecosystem in Kenya's off-grid solar sector, document how the market's rapid expansion has not been accompanied by an equally rapid development of a structured after-sales maintenance and repair ecosystem: most companies focus on the initial sale and distribution of systems, while the management

of breakdowns and component deterioration over time remains largely left to informal channels or is entirely absent. The authors identify a twofold nature to the problem: on the one hand, the absence of harmonized technical standards among different manufacturers makes it difficult to train technicians capable of working on systems from different brands without distinction; on the other hand, the scarcity of certified personnel in the area, exacerbated by the geographic dispersion of demand already discussed in Section 3.4 of the previous Chapter, makes it economically unsustainable for companies to maintain a comprehensive service network in the most remote rural areas. This shortcoming undermines consumer confidence in the long term, a critical factor for a pay-as-you-go (PAYG) business model, which relies on the continuity of the contractual relationship between the company and the customer for the entire duration of the instalment plan: a system that repeatedly malfunctions without the possibility of timely repair fundamentally undermines the customer's willingness to continue making payments, with direct repercussions on the default rates discussed later in this Section. (Harrington & Wambugu, 2021)

Closely related to this first point is the issue of managing the end of a product's life. In an ethnographic study conducted in Kenya, Cross and Murray document what they call the "afterlives" of solar systems: panels, batteries, and electronic components that, once broken or obsolete, do not enter any formal collection or recycling channels but are recovered, repaired, and reused through informal networks of local artisans and repairers. This phenomenon is part of the broader tradition of the informal repair economy typical of the Kenyan urban context (the so-called "jua kali[33]" sector), often operating outside the scope of the companies that originally sold these products (see Figure 10).

[33] The term was originally coined because these artisans work long hours under the scorching Nairobi sun. Jua Kali directly translates to Hot Sun. Recently however, as recently as last week, we had the opportunity to learn about the dual meaning of the term Jua Kali. (Kinuthia, s.d.)

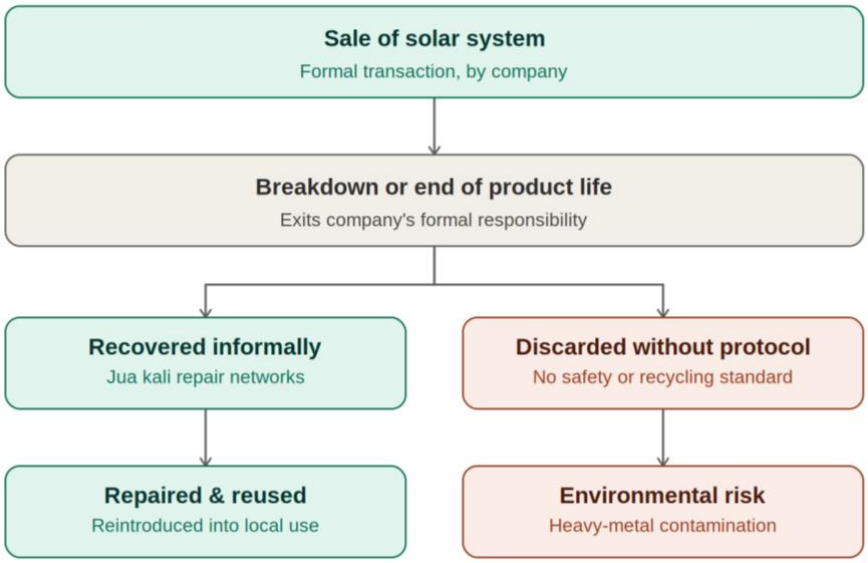


Figure 10: The "afterlife" pathway of off-grid solar products in Kenya. Author's own elaboration, based on Cross & Murray (2018)

The authors emphasize that this informal repair economy fulfils a real social and economic function, generating income and spreading technical skills throughout the region, yet at the same time operates in a near-total regulatory vacuum: the lack of safe disposal protocols for lead-acid or lithium-ion batteries exposes both repairers and the surrounding environment to risks of heavy metal contamination—an issue that manufacturers, focused on the initial sale, tend not to consider part of their responsibility (Cross & Murray, 2018).

This phenomenon represents an additional, albeit unplanned, form of local value creation and job generation, which in some ways aligns with the logic of functional upgrading discussed in Section 3.3, since it is precisely during the repair phase that the most spontaneous form of local technical expertise is observed. However, the lack of a structured approach to managing the end-of-life phase of products poses an environmental sustainability issue that the cluster, in its current form, has not yet addressed in a systematic manner, and which remains outside the scope of responsibility of both the companies and the public institutions involved.

A second set of concerns relates to the financial and social sustainability of the PAYG model itself. The mechanism underlying this model, as described in Section 2.4, is based

on the same mobile money infrastructure that Jack and Suri (2014) identify as a tool for reducing transaction costs and expanding risk-sharing networks among Kenyan households. It is precisely this ability to manage payments remotely, which enables purchases to be paid in instalments, that also makes it technically possible to remotely deactivate the system in the event of nonpayment (see Figure 11).

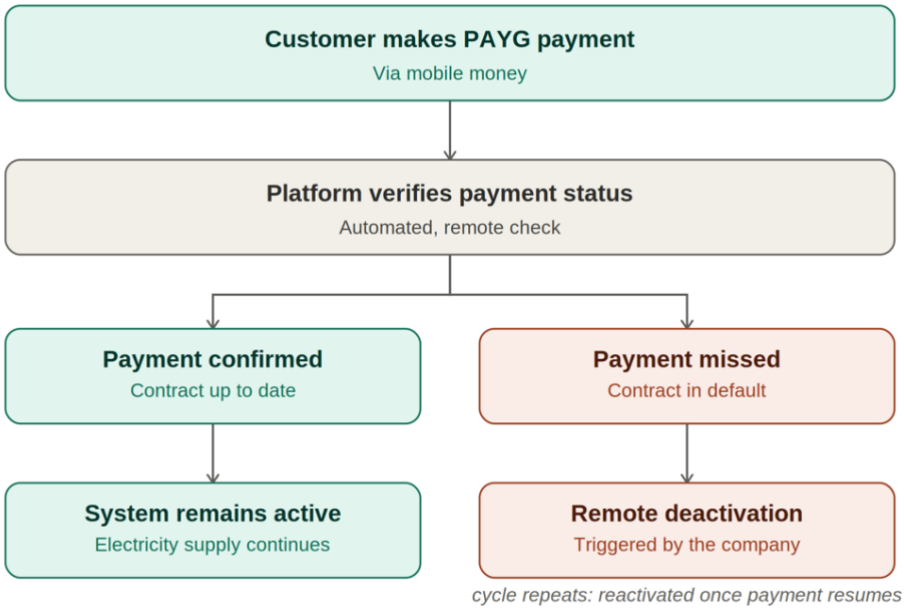


Figure 11: The PAYG remote-control mechanism as a financial discipline instrument. Author's own elaboration, based on the PAYG mechanism described in Section 2.4 and Jack & Suri (2014).

The same tool that, as discussed in Section 2.4, has made it possible to overcome the barrier of access to formal credit for low-income households thus also constitutes the channel through which the company exercises direct and immediate control over the availability of the sold item until the payment plan is fully settled. This configuration raises a question of social sustainability that ties directly into the points discussed in Section 3.3 regarding Radley and Lehmann-Grube (2022). Regarding the relationship between the expansion of off-grid solar power and economic development, the authors highlight the need for a more careful analysis of the unequal distribution of benefits generated by the sector among the various actors in the supply chain, as well as the not always transparent role of foreign companies in value capture. Applied to the remote

control mechanism described here, this point suggests that the contractual relationship between the company and the end customer should not be taken for granted as balanced: the power asymmetry between a company equipped with digital infrastructure and remote control capabilities and a rural customer with limited individual bargaining power represents a dimension of the cluster's sustainability that the mere growth in the number of connections and companies, discussed in the preceding paragraphs, is insufficient to guarantee.

Added to these challenges is a macroeconomic vulnerability, a direct consequence of the persistent dependence on imports of components, as already discussed in Section 3.3 with reference to Bhamidipati et al. (2021). If the production of photovoltaic panels and electronic components remains concentrated outside the African continent, as that data showed, the final cost of the systems sold to Kenyan customers remains structurally exposed to exchange rate volatility and international transportation costs, variables that none of the downstream stages of the supply chain, however locally rooted, is in a position to control. This is, in some ways, a paradoxical risk, because a sector created to reduce rural households' dependence on traditional energy sources and their variable costs remains itself exposed, albeit indirectly, to price shocks of a similar nature, simply shifted upstream in the supply chain.

Finally, one last area of vulnerability concerns the institutional dimension, which was already discussed in Section 3.1 with reference to the administrative devolution process initiated by the 2010 Kenyan Constitution. Volkert and Klagge (2022) highlighted how the transfer of energy planning responsibilities to county governments had not been accompanied by adequate development of technical and financial capacity at the local level, leading to overlapping jurisdictions between the central and local levels. Applied to the specific context of the Nairobi cluster, this lack of multilevel institutional coordination poses a risk to its long-term sustainability. Chapter I identified support institutions, namely, regulatory bodies, universities, and trade associations, as one of the foundational pillars of a mature cluster, capable of absorbing external shocks precisely because of the density of the institutional relationships that underpin it. If this institutional framework remains incomplete, the resilience that theory attributes to

clusters compared to isolated firms cannot be considered fully established in the case of Nairobi but should rather be understood as an ongoing process.

Taken together, these critical issues, the gap in the after-sales service and end-of-life product management ecosystem, the financial and social tensions inherent in the PAYG model, the macroeconomic exposure linked to dependence on imported components, and the incompleteness of multi-level institutional coordination do not contradict the proposed interpretation of the Nairobi ecosystem as an energy cluster but rather support its maturity. The Nairobi cluster still exhibits an incomplete configuration relative to the theoretical model outlined in Chapter I: dense in terms of the concentration of firms, investors, and supporting institutions, as discussed in Section 3.2, but still incomplete in terms of the economic, environmental, and social resilience that classical theory attributes to fully mature clusters. This tension between organizational maturity and structural fragility suggests that Cluster Theory requires adaptation to fully account for cases of development driven by international capital in contexts where institutions are still in the process of consolidation.

Chapter IV Policy and implications

4.1 Cluster theory in light of the Nairobi case

A comparison between the Cluster Theory presented in Chapter I and the empirical case reconstructed in Chapter III provides a picture of partial confirmation, which can be summarized in four points.

A comparison with the Cluster Theory presented in “The Structure of Actors” (Section 3.2) confirms Porter’s taxonomy, with one variation: the core of the cluster is not made up of widespread SMEs, as in the Marshallian model, but of a small number of multinational firms. This is not an exception to the theory, but a “few-firm-driven” variant already anticipated in the literature on clusters in developing countries. Chapter I and the empirical case study presented in Chapter III provide a picture of partial confirmation, which can be summarized in four points.

Becattini’s socio-territorial component is indirectly confirmed: the social capital underpinning the cluster was not generated endogenously by the energy sector but was inherited from the pre-existing “Silicon Savannah” ecosystem (Section 3.2). This suggests that, in urban contexts with an entrepreneurial ecosystem that is already mature in other sectors, the community component of a new sectoral cluster may form through inheritance rather than through autonomous generation.

Upgrading (Section 3.3) is selective: it is robust on a functional and cross-sectoral basis but absent on a product- and process-based basis, with the manufacturing sector remaining structurally outside the continent. This pattern is consistent with a financial structure dominated by venture capital geared toward rapid growth rather than long-term industrial investment.

Finally, resilience (Section 3.4) represents the most marked deviation from theory: the cluster’s organizational density has not yet translated into technical, financial, and institutional resilience. Classical theory treats relational density as a sufficient condition for resilience; the Nairobi case suggests that it is a necessary but not sufficient condition, contingent upon a supporting infrastructure that is still under construction.

These four perspectives converge on the idea that Cluster Theory accurately describes the organizational structure of the Nairobi phenomenon but requires adaptation to fully account for it in a development context driven by international capital and institutions that are still in the process of consolidation, an adaptation that the policies discussed in the following paragraph can help address.

4.2 Policy implications for cluster development

Porter's definition of a cluster, as discussed in Chapter I, identifies three essential local conditions: a critical mass of participants sufficient to generate relationships among workers, firms, and other economic agents; a growing division of labor between generalist firms and specialized suppliers; and a long-term commitment made possible by mutual trust and appropriate institutions. Section 4.1 showed how the Nairobi cluster still falls short with respect to each of these three conditions.

The core of the Nairobi cluster, as discussed in Section 4.1, remains today composed of a small number of multinational companies, not the broad population of participants that Porter's definition presupposes as a basic condition. The first signs of expansion, observed in Section 3.3 in the movement of personnel toward second-generation startups, remain sporadic, and there is a risk that they will remain so indefinitely: a former employee of a leading company who identifies a business opportunity currently has access to the same general-purpose incubation spaces (iHub, Nailab, Section 3.2) as any other digital entrepreneur in the city, without any support specifically tailored to the energy sector's needs, seed capital for prototyping hardware, not just software; access to a testing laboratory such as the one at the Strathmore Energy Research Center; and contacts with distributors already active in the area. A dedicated incubation program, distinct from general-purpose ones, would fill this specific gap. A second, complementary tool would address the demand side rather than the supply side: public procurement programs, such as the electrification of schools, health clinics, and rural administrative offices through tenders reserved for small and medium-sized enterprises, would create a protected initial demand, reducing the risk that currently discourages the entry of new operators lacking the scale and reputation of leading firms. This is the same type of public intervention that the literature on clusters in developing countries,

cited in Section 1.3 regarding Rodríguez-Clare, identifies as necessary where the market alone does not generate the required critical mass of participants: a collective action problem that no single firm has an incentive to solve on its own, because the benefits of a larger cluster are distributed among all participants, not just those who bear the initial cost. It is worth acknowledging, however, a limitation of this type of policy: an overly rapid expansion of the critical mass, without the quality standards discussed below, would risk reproducing on a larger scale the very same technical fragmentation that currently undermines consumer confidence (Section 3.5), the numerical growth of participants is therefore not an objective to be pursued in isolation from Porter's other two conditions.

Porter's second condition assumes that a layer of specialized suppliers develops around leading firms, not merely distributors and installers, as discussed in Section 3.3, but firms that produce intermediate components for the entire cluster, not just for a single client firm. Today, this layer is virtually nonexistent: the production of panels and electronic components remains outside the continent (Bhamidipati et al., Section 3.3), and local firms are limited to the final stages of the supply chain. A realistic policy would not aim, in the short term, at the production of photovoltaic cells, a goal that is out of reach given the lack of adequate capital and expertise, and in any case unlikely to be competitive given the economies of scale of Asian manufacturing, but rather at more accessible intermediate stages: the assembly of battery packs, the production of control units, wiring, and mounting structures. Kenya already has a potentially reusable tool for this purpose. The Export Processing Zones established to attract export-oriented light manufacturing. Extending the tax incentives already in place for those zones to companies that invest specifically in these intermediate stages of the solar supply chain would offer an immediately available institutional starting point, rather than a tool that would have to be built from scratch. A second element, complementary to tax incentives, concerns technical training: the model already tested through the collaboration between the Strathmore Energy Research Center and the Kenya Off-Grid Solar Access Project (Section 3.3) could be expanded to include a track specifically dedicated to these intermediate manufacturing skills. One point, however, deserves explicit attention: for this tier of suppliers to truly become "specialized" in the

theoretical sense, that is, capable of serving the entire cluster, rather than a single client firm in a relationship of substantial dependence, incentive policies should explicitly reward suppliers who diversify their customer base across multiple firms within the cluster, for example by making the tax incentives mentioned above contingent upon demonstrating contracts with more than one buyer. Otherwise, there is a real risk that these suppliers will remain vertically integrated within a single leading firm, replicating the same concentration of decision-making already observed at the core of the cluster, without generating the market for intermediate inputs that theory associates with a mature cluster.

Porter's third condition concerns mutual trust supported by institutions, not generic ones, but those capable of ensuring the continuity of relationships among the cluster's stakeholders over time. Today, this function is fragmented among EPRA, the Ministry of Energy, and international cooperation agencies (Section 3.2), without a dedicated coordination body specifically for the off-grid energy cluster. An industry association, modelled after the trade associations that theory identifies as constitutive institutions of a mature cluster, that formally brings together companies, investors, Strathmore SERC, and the regulator would provide the cluster with a permanent forum serving at least three concrete functions:

- The definition of technical interoperability standards, as already discussed in Section 3.5, which would otherwise be difficult to impose from above without the direct involvement of the companies that would have to adopt them.
- A mechanism for resolving disputes between companies and customers regarding PAYG contracts, which would be less burdensome than individual legal litigation for a low-income rural customer.
- A shared data platform on failure and complaint rates by brand and model, which would restore functionality to the quality signalling mechanism currently compromised by the absence of common standards.

Agencies already present in the ecosystem (GIZ and Power Africa, discussed in Section 3.2) would likely have both the interest and the resources to fund an initial technical secretariat, thereby reducing the startup costs that would otherwise discourage

companies from organizing themselves independently. Here, too, however, it is worth explicitly addressing a risk. If the governance of this association were to end up being dominated by the very multinational companies that today constitute the core of the cluster, the institution would risk reinforcing the critical mass imbalance discussed at the outset, rather than correcting it. A representation rule that reserves a minimum number of seats for small businesses and representatives of the informal “jua kali” repair network (Section 3.5) would help prevent this outcome.

The three conditions just discussed presuppose a context that is already partially primed to accommodate them: the social capital inherited from the Silicon Savannah ecosystem, discussed in Section 4.1, has provided Nairobi with a starting point that does not exist elsewhere. This is a form of cumulative advantage that tends to reinforce itself over time, rather than automatically spreading elsewhere simply because market conditions would justify it. Cities like Mombasa or Kisumu, though endowed with a significant commercial base, lack the same layer of entrepreneurial hubs and mentorship networks. Anyone wishing to replicate the Nairobi model elsewhere should therefore factor in a separate, preliminary investment in building a general-purpose entrepreneurial ecosystem, even before applying the three specific policies for the energy sector just discussed, policies that in Nairobi were able to build on ground that had already been partially prepared, and that elsewhere would likely need to be preceded by, rather than accompanied by, that type of investment.

4.3 Global relevance

The case of the Nairobi off-grid cluster is not only descriptive of Kenya’s energy sector but also offers a useful vantage point for three broader debates on Cluster Theory. First, the debate regarding its application in contexts other than the manufacturing industrial districts upon which it was historically built; second, the debate on energy transition trajectories in developing countries; and finally, the debate on the sequence in which different clusters may form within the same territory over time.

On the first front, the relevant literature presented in Chapter I, from Marshall to Becattini’s Italian industrial districts, up to Porter, has developed almost entirely around cases of mature manufacturing: textile, mechanical, and automotive districts, often in

high-income economies or at advanced stages of industrialization, as the examples discussed in the course material also demonstrate (from the “Motor Valleys” of Emilia-Romagna to China’s Pearl River Districts). The Nairobi cluster, on the other hand, belongs to a different category, one that classical theory did not explicitly foresee: a cluster built around a service, decentralized energy access, rather than a mature, manufactured product, in a context where actual manufacturing remains, as discussed in Section 3.3, almost entirely outside the continent. The three deviations identified in Section 4.1, the “few-firm-driven” enterprise scale, inherited social capital rather than endogenously generated capital, and selective upgrading that favours the least capital-intensive stages, are therefore not merely peculiarities of the Kenyan case, but indications of how Cluster Theory may require systematic adaptation when applied to service clusters in developing economies, where initial capital typically comes from international investors rather than from a pre-existing local entrepreneurial base. This is an area where the literature remains limited, and to which the case of Nairobi offers a concrete empirical contribution: a cluster that starts out “light", with little fixed capital and a great deal of digital and financial intermediation, probably represents a more realistic trajectory for many developing economies than the classic manufacturing model, simply because it requires a much smaller initial endowment of physical capital.

On the second front, the comparison between Kenya and Tanzania proposed by Ondraczek, which was already discussed in Section 3.1, helps to place the significance of this case in a comparative perspective. The two countries share essentially equivalent solar resource endowments, yet only Kenya has developed a global-scale off-grid market, a divergence that Ondraczek attributes to factors of demand and product availability rather than natural resources. Specifically in Nairobi, the existence of a pre-existing digital entrepreneurial ecosystem capable of providing social capital, expertise, and investor networks to the emerging off-grid energy sector, a condition that, as discussed in Section 4.2, cannot be replaced by solar resource endowment or potential demand alone. In other words, the question “why Kenya and not Tanzania” finds, in light of Cluster Theory, a more precise answer than that available in the energy literature alone: it is not market demand in and of itself that explains the divergence, but rather the presence of a cluster capable of transforming that demand into an organized sector.

This observation opens up a third line of inquiry, one that is more specific but, in some ways, the most original among those discussed in this Section: the Nairobi case suggests that clusters do not necessarily emerge in isolation, but can form sequentially within the same territory, with a mature cluster creating the preconditions for the emergence of a subsequent cluster in an entirely different sector. The social capital inherited from the Silicon Savannah ecosystem, discussed in Section 4.1, is not a generic phenomenon: it is the direct result of a specific technological and financial cluster, the one built around M-Pesa and mobile money beginning in the mid-2000s, which preceded the emergence of the energy cluster analysed here by a decade. The PAYG instalment financing mechanism, discussed in Section 2.4 and revisited in Section 3.2, could not have taken hold in Nairobi as quickly without an already widespread digital payment infrastructure, tested on a national scale, and a community of developers and entrepreneurs already accustomed to building digital financial products. The possibility that a mature Cluster Theory could serve as an enabling platform for the emergence of subsequent clusters in adjacent sectors could prove particularly relevant for other African urban hubs (Lagos, Kigali, Kampala) that have well-established technology ecosystems in one sector and are potentially poised to generate subsequent sector-specific clusters following a trajectory similar to that of Nairobi.

This interpretation has broader implications for the debate on the energy transition in developing countries, which often tends to focus on the technological and financial aspects of energy access, particularly technology costs, financing mechanisms, and regulatory frameworks, while treating the local business environment as a background variable rather than a key explanatory factor. The Nairobi case, however, suggests that a country's ability to develop a mature off-grid sector depends significantly on dynamics identified by the literature on clusters in other contexts. These dynamics include spatial concentration, workforce mobility, supporting institutions, and the legacy of social capital from previous cluster, factors that the literature on energy access, with exceptions such as Ogeya and Lambe (Section 3.2), has so far incorporated only partially.

As shown in Section 4.1, the Nairobi cluster remains a case of partial organizational maturity: it is dense in terms of actors but still fragile in terms of technical, financial, and

institutional resilience. The implications proposed in this Section should therefore be read as guidance on the direction in which theory and policy should move, not as a description of a fully developed model ready for export. A further limitation concerns the generalizability of the “inter-cluster inheritance” mechanism just discussed: for now, it is a plausible hypothesis based on a single case study, not a causal relationship verified across a broader sample of cities, a case study, however rich, cannot on its own distinguish between a genuine dynamic of cumulative inheritance and a mere historical coincidence between the growth of two sectors in the same city. It is precisely for this reason that the comparative research agenda outlined above represents the most natural next step following the conclusions of this thesis, rather than an optional extension.

Conclusion

This thesis analysed the case of the Nairobi off-grid cluster as a lens through which to reexamine Cluster Theory in a context, decentralized energy access in sub-Saharan Africa, that the classical literature on industrial districts and technology clusters did not explicitly anticipate. The line of argument, summarized in the very title of the thesis, followed a precise trajectory: from the market failure that characterizes energy access in developing countries (Chapter II and III) to the social and industrial spillover effects that a cluster-based organization is capable of generating where the market, on its own, fails to do so (Chapters III and IV).

Chapter II outlined the theoretical framework, showing how the concept of cluster, from Marshallian externalities to Porter's codification, and on to the adaptations proposed by the literature on clusters in developing countries, offers a framework capable of explaining not only the agglomeration of mature manufacturing firms but also, with the appropriate adaptations, the emergence of entrepreneurial configurations centred around a service such as decentralized energy. Chapter III situated this theoretical framework within the specific context of the sub-Saharan energy market failure: fragmented electricity grids, concentrated around urban centres and unable to reach a dispersed rural demand, have created the economic space in which off-grid solutions, and in particular the pay-as-you-go mode, have established themselves as a response capable of circumvention, rather than resolving, the underlying coordination problem.

Chapter IV provided an empirical analysis of the case, showing how the off-grid ecosystem concentrated in Nairobi only partially meets the classic definition of a cluster: dense in terms of the structure of its actors, companies, investors, academic institutions, and international cooperation organizations, all of which are mapped in Section 4.2, and capable of generating genuine industrial and social spillovers, as discussed in Section 4.3, but marked by three significant deviations from the initial theoretical model: an entrepreneurial core driven by a small number of multinational corporations rather than by a widespread population of local SMEs; social capital inherited from the pre-existing Silicon Savannah technology ecosystem rather than generated endogenously by the energy sector; a process of selective upgrading, solid in functional and cross-sectoral

terms but still absent in the manufacturing sector. Section 4.5 also documented how this organizational density has not yet translated into full technical, financial, and institutional resilience, a limitation that Chapter IV proposed to interpret not as an anomaly specific to the Nairobi case, but as an indication that the theory requires systematic adaptation when applied to service clusters driven by international capital in contexts where institutions are still in the process of consolidation.

This interpretation gives rise to the implications discussed in Chapter IV: policies designed not to correct individual operational problems in the sector, but to complete the cluster along the three defining dimensions identified by Porter, critical mass of participants, division of labor between generalist firms and specialized suppliers, and long-term trust supported by appropriate institutions, and a comparative analysis, in Section 4.3, which suggested that the Nairobi-specific advantage stems not only from demand and resource conditions but also from the legacy of a previous technological and financial cluster, the one built around M-Pesa, whose infrastructure enabled the PAYG model to take hold with a speed that would be difficult to replicate elsewhere without a comparable prior layer of social capital.

Ultimately, the Nairobi energy cluster demonstrates how a market failure—the inability of the centralized power grid to reach a dispersed, low-income customer base, can, given the right entrepreneurial conditions, generate an organized response capable of producing real industrial and social spillovers, even though the process remains incomplete compared to the full theoretical model of a mature cluster. It is in this tension between concrete results and ongoing maturation that, in conclusion, the theoretical and practical significance of the analysed case lies.

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