



**Infrastructure Resilience against Vandalism: A Case Study of Solar Street Lighting in
Selected Gauteng Metros**

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Abstract

Solar Street lighting vandalism in Gauteng metros reveals a complex problem that technical fixes alone cannot solve. This study examines why infrastructure resilience strategies fail when they treat vandalism as merely hardware or a security issue, rather than a sociotechnical systems challenge. The research investigates the drivers of vandalism affecting solar street lighting in Johannesburg and Tshwane, evaluates current response strategies, explores community participation dynamics, and identifies necessary governance reforms.

Using an interpretivist qualitative approach, 13 semi-structured interviews were conducted with municipal engineers, and original equipment manufacturers. Thematic analysis, guided by socio-ecological-technical-systems (SETS) framework, revealed that vandalism stems from interconnected social, institutional, and technical vulnerabilities. Economic desperation, political frustration, institutional fragmentation, and poor community engagement create conditions where vandalism becomes rational or expressive.

The findings demonstrate that fragmented, reactive approaches merely shift vulnerability rather than building resilience. Sustainable solutions require integrated strategies that combine robust technical design, transparent governance, meaningful community participation, and cross-departmental coordination. Gauteng's challenging context of migration, poverty and resource constraints makes it an ideal proving ground. If resilience orientated systems-thinking approaches succeed here, they can be scaled across South Africa. The study contributes a practical framework for embedding resilience thinking into urban infrastructure planning and management.

Keywords

Infrastructure resilience; vandalism; solar street lighting; community participation; governance coordination

Plagiarism Declaration

I declare that this research project is my own work. It is submitted in partial fulfilment of the requirements for the degree of Master of Business Administration at the Gordon Institute of Business Science, University of Pretoria. It has not been submitted before for any degree or examination in any other University. I further declare that I have obtained the necessary authorisation and consent to carry out this research.

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Chapter 1: Introduction

1.1 Background

Infrastructure systems play a significant role in sustaining quality of life, service delivery, and economic growth in both developing and developed nations. Their effective functioning sustains productivity, social stability, and equitable development. Theft, vandalism, and sabotage, however, critically undermine infrastructure resilience, particularly in contexts with governance weaknesses and resource constraints. South Africa exemplifies these challenges, especially in the energy and transport sectors, where public lighting and electrical networks face persistent criminal activity and neglect (Musavengane et al., 2020). These disruptions generate direct financial losses while creating wider societal impacts that compromise urban safety and economic productivity.

Infrastructure vandalism has escalated globally as a critical governance and security concern. In the United States, intentional attacks on telecommunications infrastructure surged in late 2024, with over 5,770 incidents affecting 1.5 million customers and costing providers millions in infrastructure losses and insurance claims (National Cable and Telecommunications Association [NCTA], 2025). Uganda experienced significant connectivity disruptions across urban centres due to copper and fibre cable theft (Ecofin Agency, 2023). Infrastructure sabotage targeting energy grids, telecommunications systems, and transportation networks has intensified alongside technological interconnectivity and urban expansion (Kapucu et al., 2024). These disruptions strain public finances while exposing institutional co-ordination vulnerabilities and crisis preparedness gaps. Bhati and Agarwal (2021) argued that such incidents reflect not merely technical vulnerabilities but the institutionalisation of systemic inequalities and insufficient community involvement in infrastructure management.

In Africa, infrastructure vandalism and theft show broader governance and socioeconomic crises. Nigeria's power sector illustrates this pattern, where cable and transformer theft causes billions in annual losses and threatens energy reliability (Mugari & Obioha, 2024). South Africa faces similar challenges within state-owned companies like Eskom, where copper theft and infrastructure sabotage disrupt power supply while straining maintenance

and security budgets (Business Tech, 2024). The emergence of organised crime syndicates specialising in infrastructure theft has created particularly complex enforcement challenges, overwhelming law enforcement capacity through their scale and co-ordination (Brayne et al., 2023). These patterns reveal deeper social and institutional deficits, including inequality, low community trust, and ineffective participatory governance, demonstrating how governance fragility, inequality, and institutional fragmentation collectively weaken infrastructure resilience (Fobosi & Malima, 2025; Musavengane et al., 2020).

The transition toward renewable energy and decentralised systems offers opportunities for improved resilience. Solar-powered public lighting systems promise improved access, reduced grid dependence, and support for urban decarbonisation (Skosana et al., 2023). South African metropolitan municipalities, including Johannesburg and Tshwane, have invested substantially in solar street lighting as part of sustainable infrastructure strategies representing broader commitments to green infrastructure and renewable energy transitions (Mirzania et al., 2023). Nevertheless, success depends not only on technological innovation but equally on governance quality, maintenance practices, and community stewardship. International assessments of solar street lighting systems have predominantly focused on technical and economic efficiency, yet limited attention is given to system vulnerability to vandalism or sustainability in hostile urban environments (Belloni et al., 2024).

Infrastructure vandalism carries profound social equity implications, with marginalised urban communities disproportionately suffering from failed or poorly maintained infrastructure. These communities, already experiencing service delivery shortages, face compounded disadvantages when infrastructure fails. The resulting insecurity and exclusion cycles perpetuate spatial inequality patterns characteristic of South African cities (Lunga et al., 2025). Consequently, solar street lighting transcends technical or environmental intervention status, intersecting with broader questions of social justice, inclusion, and equitable development. Success requires integrating governance reform, community engagement and social justice considerations within infrastructure planning (Bibri & Krogstie, 2021).

Addressing infrastructure vandalism demands comprehensive approaches acknowledging both immediate security needs and underlying structural causes. Technical solutions like reinforced mounting systems and tamper-proof designs represent necessary but insufficient responses. Equally important are interventions addressing unemployment, inequality, and

social exclusion, driving vandalism behaviours. Understanding vandalism's interaction with sociopolitical and institutional dimensions proves essential for advancing sustainable urban development and resilient infrastructure in South Africa.

This study explores how vandalism affects solar street light system sustainability and resilience in Johannesburg and Tshwane, contributing to broader infrastructure governance and urban resilience debates in the Global South. The investigation addresses critical gaps in understanding the complex interplay between technological solutions, governance structures, and community dynamics in protecting public infrastructure investments.

1.2 Research Problem

Despite growing investment in solar street light infrastructure as part of South Africa's green infrastructure agenda, the persistence of vandalism and theft continues to undermine these systems' operational resilience and urban safety outcomes. As an example, 30 per cent of existing street lighting systems were non-functional in Johannesburg, according to Sibiya (2024). Existing responses have largely prioritised technical and security solutions such as tamper-proof designs or concrete mounting poles (Belloni et al., 2024; Newsroom Afrika, 2025). However, these measures overlook the deeper socioeconomic inequalities, weak institutional co-ordination, and limited community ownership that perpetuate infrastructure vulnerability in metropolitan contexts such as Johannesburg and Tshwane (Fobosi & Malima, 2025; Lunga et al., 2025).

The disconnect between technical interventions and social realities represents a critical theoretical and practical gap. From a theoretical perspective, resilience theory and the social-ecological-technological systems (SETS) framework indicate that infrastructure resilience emanates from interaction between social, ecological and technological dimensions (McPhearson et al., 2022). However, current approaches to solar street lighting vandalism

remain siloed in technical domains, failing to integrate the social and institutional dimensions that are pivotal for resilience (Bibri & Krogstie, 2021; Kapucu et al., 2024). Without an empirical understanding of how governance quality, community engagement and socio-technical factors interact within South African urban contexts, municipalities cannot develop effective resilience strategies (Gillard et al., 2019; Kiss et al., 2022). The consequence is a costly cycle, where renewable energy investments fail to deliver reliable services, communities lose trust in green infrastructure, and spatial inequalities deepen as marginalised areas suffer disproportionate service failures (Mugari & Obioha, 2024; Cirolia & Harber, 2021; Chirisa et al., 2016).

The study, therefore, investigates the socio-technical determinants of solar street lighting vulnerability in Johannesburg and Tshwane through four interconnected dimensions. First, it examines the socioeconomic, institutional, and spatial drivers of infrastructure vandalism. Second, it evaluates the effectiveness of current technical and institutional strategies in mitigating vandalism. Third, it explores how community participation influences infrastructure resilience outcomes. Fourth, it identifies governance reforms needed for sustainable solar infrastructure management in vandalism-prone contexts. Through this multilevel investigation, the study develops an integrated resilience framework that synthesises technical design, institutional co-ordination, and social stewardship.

1.3 Business Need for the Study

While comprehensive financial data for solar street lighting vandalism are not yet available due to the relatively recent rollout of these systems, the scale of losses from conventional

street lighting in Gauteng municipalities already signals the magnitude of the risk. According to the City of Johannesburg (2024), the municipality incurred R3.45 billion in non-technical losses, including theft, vandalism, and illegal connections, thus contributing to the 30 per cent street light system failure rate mentioned earlier. These patterns indicate that without proactive resilience measures, solar street light systems will likely face similar or greater exposure, given the additional value of components such as batteries and photovoltaic panels.

The business imperative to anticipate and mitigate infrastructure vandalism is compelling. In Johannesburg, over R500 million annually in theft and vandalism losses, including City power reporting R2 billion in non-technical losses and the Road Agencies carrying a R70 million repair backlog (Masungwini, 2023; City of Johannesburg, 2021, 2025). Tshwane faces similar pressures, with electricity theft losses approaching R470 million annually and a 2025 asset protection budget exceeding R500 million (City of Tshwane, 2022; Goba, 2025). These recurring costs shorten asset lifespans, divert capital from expansion into replacement, and complicate budgeting and service delivery continuity (South African Institution of Civil Engineering, 2017). Strategically, persistent infrastructure vulnerability threatens access to climate finance, as the climate bonds initiative's resilience-integrated principles need issuers to demonstrate climate risk assessment, resilience-integrated design, and performance monitoring to maintain investor confidence (Climate Bonds Initiative, Climate Resilience Consulting, & World Resources Institute, 2019).

As such, this research responds to a critical business and policy need, i.e. to develop evidence-based, cost-effective resilience strategies that integrate technical safeguards, community participation, and governance reform. By strengthening asset protection and

public trust, municipalities can transform solar street lighting from a possible liability into a sustainable and financeable infrastructure asset class.

1.4 Theoretical Need for the Study

Even though most of the published literature on solar street lighting concerns technical performance, procurement, and lifecycle costs, there is an evident theoretical gap in describing vandalism as a socio-technical and governance issue rather than a simply technical failure. Available studies focus on engineering and policy solutions at the expense of the social motives behind theft, neglect, and destruction of protests, with this study set to fill this gap (Kapucu et al., 2024; Belloni et al., 2024; Rodina et al., 2024; Liu et al., 2022).

The theoretical requirement is thus two-fold. To start with, resilience theory, which was initially developed within the ecological research (Holling, 1973), will have to be expanded here and explicitly explain sociopolitical forces of infrastructural failure, such as the role of inequality, lack of trust, and political activism in the interaction with material vulnerabilities (McPhearson et al., 2022; Bibri & Krogstie, 2021). In this view, vandalism emerges not as an isolated act of theft but as a systemic outcome of intersecting inequities, institutional weaknesses, and eroding civic trust (Rodina et al., 2024). Secondly, the theoretical linkage between governance, social capital and resilience becomes critical. As Liu et al. (2022) demonstrate, social capital through norms of trust, reciprocity and civic participation plays an important role in encouraging community-based resilience. Similarly, Östh et al. (2018) identify bridging social capital (ties that connect diverse groups) as a stronger predictor of resilience capacity than bonding ties, highlighting the need for inclusive governance and participatory

stewardship. Applying these principles to South African urban infrastructure contexts suggests that participatory systems, when tokenistic or exclusionary, erode ownership and amplify infrastructure vulnerability. This brings out the necessity of having a theoretical framework that recognises and incorporates the social legitimacy, institutional capacity, and technical design.

By filling this gap in theory, the research will (a) generate a conceptual model, connecting governance, community stewardship, and technical design to the outcome of vulnerability and resilience; (b) provide a theoretical foundation for integrating resilience principles to procurement, maintenance and asset management policies; and (c) offer a transferable explanatory framework to other developing cities where vandalism and governmental weakness coexist. This study aligns with the overall resilience literature, which highlights the interrelationship between social and technical systems in establishing the long-term sustainability of infrastructure (McPhearson et al., 2022; Bibri & Krogstie, 2021).

1.5 Research Significance

This study makes three distinct contributions to infrastructure resilience scholarship and practice.

Theoretical contribution: While existing literature treats vandalism as either a technical failure (requiring engineering solutions) or a criminal act (requiring enforcement), this study reconceptualises it as an emergent property of socio-technical system dynamics. By applying the SETS framework to solar street lighting in African urban contexts, the research extends

resilience theory beyond its traditional focus on natural hazards to encompass the intersection of social inequality, institutional capacity, and technological vulnerability.

Empirical contribution: The study provides the first systematic analysis of how vandalism affects renewable energy infrastructure resilience in South African metros. Through stakeholder perspectives from Johannesburg and Tshwane, it documents the complex interplay between material incentives (component value), spatial vulnerability (location-based risk), and governance failures that existing technical assessments overlook (Belloni et al., 2024). This evidence base fills a critical gap in understanding why technically sound solar systems fail in socially complex environments.

Practical Contribution: For policymakers and infrastructure managers, the research provides an integrated resilience framework that moves beyond reactive responses to proactive system design. By demonstrating how community participation, institutional co-ordination, and technical innovation must function together, it offers actionable strategies for protecting municipal asset infrastructure that is at risk. This directly supports South Africa's renewable energy transition goals while offering transferable lessons for other Global South cities confronting similar challenges.

The timing of the study is critical as municipalities increasingly adopt solar infrastructure without corresponding governance adaptations, risking the sustainability of climate investments across Africa.

Figure 1 below represents a conceptual framework, showing how vandalism drivers necessitate institutional and technical responses that, when mediated by community

participation, can generate infrastructure resilience and sustained service delivery. The feedback loop from outcomes back to governance represents continuous learning and adaptation for long-term sustainability. Drawing on the social-ecological-technological systems (SETS) theory, the framework guides the investigation of how socio-technical integration can enhance infrastructure resilience in complex urban environments.

1.6 Conceptual Framework

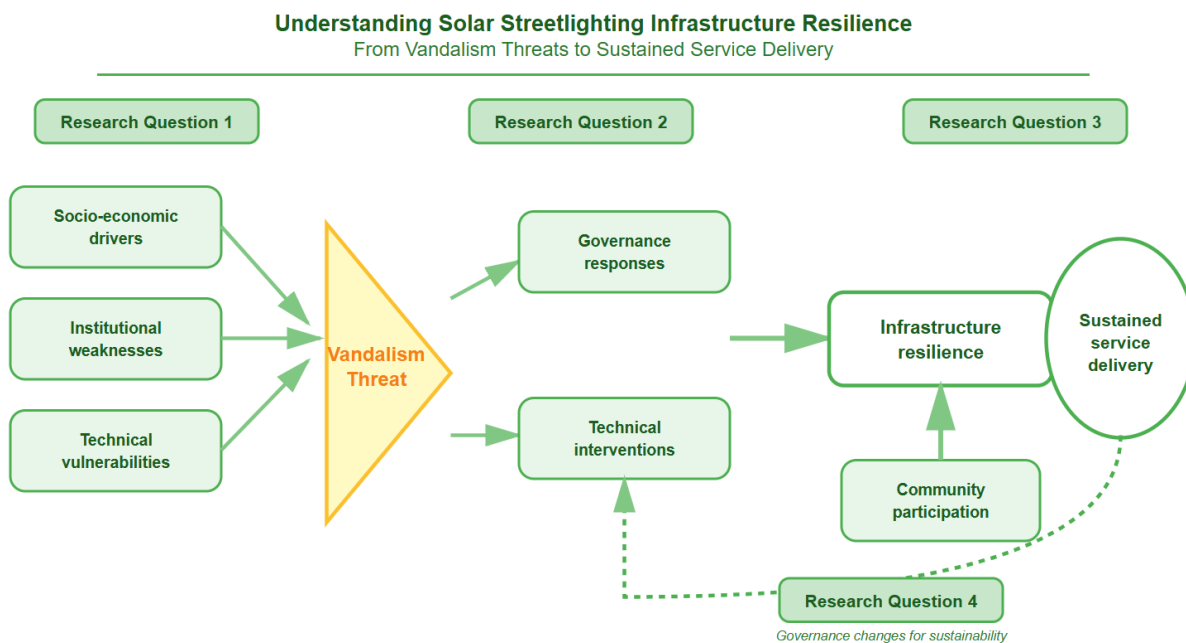


Figure 1: Conceptual framework of the study

1.7 Research Objectives

- To examine the institutional, technical, and community factors contributing to vandalism of solar street lighting in Gauteng's metropolitan areas.

- To assess how governance structures, community participation and social capital dynamics influence the resilience of solar street light systems.
- To evaluate the effectiveness and limitations of current policy, as well as technical interventions addressing vandalism.
- To develop an integrated resilience framework that links governance, community stewardship and technical design for sustainable solar street lighting in South African urban contexts.

1.8 Scope and Context of the Study

This research is situated within the context of solar street light projects in the metropolitan municipalities of Johannesburg and Tshwane, Gauteng. These projects are central to the metros' renewable energy and urban sustainability agendas (Mirzania et al., 2023). Gauteng, as South Africa's most urbanised and economically critical province, contributing approximately 33.2% to the national economy and housing about 25.5% of its population, provides a strategic setting for this study (*Statistics South Africa*, 2023a, 2023b).

The scope of this study is specifically confined to solar-powered public lighting (street lighting and floodlighting). This infrastructure presents a compelling socio-technical case: It is physically decentralised and embedded within communal spaces, making it both a vital public good and a highly visible, accessible target for theft and sabotage (Belloni et al., 2024). While vandalism affects various infrastructures (Business Tech, 2024; Ecofin Agency, 2023), a focused examination of solar street lights allows for an in-depth exploration of the interplay between their technical design, institutional management, and social context.

The full set of research questions is presented in Chapter 3 (Section 3.2).

Chapter 2: Literature Review

2.1 Introduction

These are issues in sub-Saharan Africa demanding attention in the form of frequent service failures, maintenance backlogs and infrastructure vandalism, which collectively threaten the reliability and sustainability of urban services (Fobosi & Malima, 2025; Lunga et al., 2025; Musavengane et al., 2020). Even though infrastructure vandalism has traditionally been defined as a technical or security issue, the current study emphasises that it is within the context of broader sociopolitical and economic systems, where it needs to be conceptualised in greater detail in terms of both theory and practice (Cirolia & Harber, 2021; Kapucu et al., 2024; Cantelmi et al., 2021).

Solar street lighting has taken a flagship role in urban sustainability policies, advancing renewable energy access and urban safety (Skosana et al., 2023; Belloni et al., 2024). However, implementation has revealed significant vulnerabilities. Cable, solar panels, and equipment theft have become widespread in Gauteng province, particularly in Johannesburg and Tshwane metros, leading to service disruption and escalating maintenance challenges. These incidents interfere with proper operation while eroding public trust in municipal governance and renewable energy initiatives.

As one of the most important considerations, the sustainability of solar street lighting systems in socio-politically complex urban environments has not been given due attention in current literature (Belloni et al., 2024; Helmrich et al., 2023; Sharifi et al., 2023; Mourtzis et al., 2020). Few studies have been conducted to establish the relationship between vandalism, community participation, and institutional governance, as they overlap and affect infrastructure outcomes within African cities. Additionally, infrastructure resilience has so far been studied in a fragmented manner: Engineering has approached it through the lens of material strength, and social science through the lens of governance and engagement with limited interaction between the two disciplines (McPhearson et al., 2022; Kim et al., 2022; Shrimpton & Balta-Ozkan, 2024).

This literature review offers a critical synthesis of existing research on urban infrastructure resilience, vandalism, community involvement, and technical solutions to identify gaps in knowledge regarding solar street lighting resilience in vandalism-prone environments. Grounded in resilience theory and socio-technical systems theory, the review presents the conceptual framework by which the interaction of social, institutional, and technical factors influences infrastructure outcomes.

The chapter is thematised and in chronological sequence, beginning with the theoretical background, then moving on to contextual vulnerabilities, followed by vandalism dynamics, then concluding with solar street lighting practice, community involvement, institutional strategies and research gaps.

2.2 Conceptualising Infrastructure Resilience

The concept of resilience has evolved incredibly because it was introduced in the field of ecology. It was originally defined as the ability of ecosystems to absorb disturbances and maintain the main functions (Holling, 1973). Over the years, the resilience theory has been applied to other research fields to fit a particular purpose, one such being in urban studies and infrastructure planning, to endure the complicated and fast urbanising natural environments. In relation to the urban infrastructure, the notion of resilience is applied to define how the system can maintain, change, and recuperate after disabilities to continue delivering the services needed (Mayar et al., 2022). Unlike traditional risk management frameworks that focus on preventing specific hazards, resilience frameworks emphasise adaptive capacity and the ability of the system to continue functioning even when being subjected to a broad field of perturbations, including natural disasters, system failures, and vandalism (Kapucu et al., 2024; Rodina et al., 2024). Resilience theory increasingly interprets infrastructural failure as institutional and governance failure rather than purely technical problems (Kapucu et al., 2024). The SETS perspective underscores how vandalism represents systemic breakdown rather than isolated criminal acts, and sees them as emerging from weak departmental co-ordination, fragmented policy execution, and inadequate maintenance systems that collectively heighten infrastructure vulnerability.

It is possible to define the notion of resilience within an urban infrastructural context in three interconnected dimensions, namely physical, functional and social. Physical resilience relates to the very property of materials and the design of being durable and strong, as well as to the protective design elements like tamper-resistant street light components. Functional resilience relates to the degree to which a system is capable of remaining functional, or quickly restoring normal operation after being disrupted, hence ensuring that important services are not impaired. The third dimension, social resilience, refers to the ability of communities, institutions, and government to adapt, co-ordinate, and provide services in the face of disturbances, particularly under the stress of weak governance and greater societal vulnerability (McPhearson et al., 2022; Helmrich et al., 2023). Together, these dimensions provide an important framework for evaluating the sensitivity of infrastructure systems in urban environments to stressors and, particularly, the stress of weak governance and greater societal vulnerability.

Urban infrastructure scholarship has further expanded the conceptualisation of resilience through the social-ecological-technological systems (SETS) framework, which provides a combined and holistic view of the interrelations between infrastructure and social, political and environmental drivers. While SETS is aware that urban infrastructure is often seen as a closed technical system, it also emphasises how there is an inherent embedding of it in social and institutional contexts (Sharifi et al., 2023; McPhearson et al., 2022). This approach reveals the inadequacy of considering infrastructure resilience and importance without considering technology, governance, and socio-environmental milieu interdependencies.

The interdependencies described by the SETS framework are illustrated by problems faced by solar street lighting systems in Johannesburg and Tshwane. While solar street lights are

praised for their energy efficiency and environmental friendliness, another important aspect that shows the vulnerability of solar street lights is their vulnerability to theft and vandalism, which cannot be sufficiently described by simple technical indicators. Social and economic inequality, poverty and the need for commodities like copper are the main reasons for theft (Qhobosheane, 2023; Fobosi & Malima, 2025; Lunga et al., 2025). In addition, the lack of both local authorities' maintenance and security capabilities predisposes these systems to being vulnerable, thus perpetuating a vicious cycle of poor governance and limited community involvement, increasing their susceptibility to vandalism and theft (Fobosi & Malima, 2025; Lunga et al., 2025).

Both resilience theory and socio-technical systems theory provide a holistic theoretical perspective of the urban infrastructure response to multiple challenges. This compounded view is especially relevant in South Africa, where infrastructure such as solar street lighting is exposed to a combination of technical, social, political and economic pressures. However, resilience is a complex concept that requires integration of technological solutions, institutional capacities and social dynamics, which must be considered collaboratively in operational resilience strategy development (Kim et al., 2022; Negri et al., 2021).

Within the Gauteng Metros, the vulnerability of solar street lighting is expressed as a disconnect between the technical design of the lighting systems and the social, economic and political context in which the systems are being deployed. For example, using infraction-sensitive hardware can help reduce some forms of crime, but does not explain socioeconomic drivers of vandalism such as poverty, unemployment and a shadow economy for stolen materials. Likewise, in the case of municipalities that have implemented technical interventions such as remote monitoring and surveillance, these interventions have been

shown to be inadequate in the absence of supporting community engagement and institutional capacity (Belloni et al., 2024; Erizaputri & Bechauf, 2025). A holistic understanding of the resilience of solar street lighting systems in Gauteng, therefore, requires an investigation of the long-term relations and co-evolution of technical, institutional and social dynamics.

Besides, in the case of applying these theories to the solar street lighting in Gauteng, one can widen the existing resilience and socio-technical systems theories. The infrastructure systems' adaptation to vandalism and other disruptions of the system analysis in an environment of weak governance, high levels of inequality, and disengagement of the community in the urban environment will aid the research project in contributing new values to the resilience of the urban infrastructure within the developing environment. Specifically, the research will analyse how social, technical, and governance strategies can be integrated to enhance the resilience of solar street lighting systems that can act as valuable lessons to other cities facing the same problems (Van Koppen et al., 2024; Rodina et al., 2024).

Having established the SETS framework for understanding infrastructure resilience (2.2), the contextual vulnerabilities that shape vandalism patterns in developing urban environments will then be examined.

2.3 Vulnerability of Urban Infrastructure in Developing Country Contexts

Socioeconomic, political, and environmental issues largely determine urban infrastructure vulnerability in developing countries. In cities with high urbanisation, poverty,

and political instability, infrastructural systems are not well-maintained and are mainly subject to various derailments, including theft and vandalism. These weaknesses point to institutional weaknesses that influence the ability of the infrastructure to work reliably and sustainably, with dismal social and economic implications (Fobosi & Malima, 2025; Lunga et al., 2025; Rodina et al., 2024).

Weakness in the infrastructure of developing countries is one of the most pressing issues that predetermines underinvestment, in terms of maintenance and repair, as a chronic phenomenon in these systems. Although governments can finance completely new infrastructure initiatives, the maintenance of new systems is often overlooked in the long term because of financial limitations, bad governance, and corruption (Fobosi & Malima, 2025). In South Africa, theft of solar street lights, copper wiring, solar panels and associated components is exacerbated by insufficient municipal funding for repairs and security installations. This suggests that poorly maintained infrastructure is more vulnerable to vandalism, which in turn reduces its operational capabilities and imposes extra costs to municipalities with constrained budgets and limited financial capacity (Kapucu et al., 2024; AGSA, 2024).

In addition to the underinvestment, socioeconomic disparities are another factor that makes the infrastructure systems vulnerable. The disparities in gaining access to the services provided by the state in South Africa build an environment where disadvantaged classes of people, who are usually disadvantaged in terms of infrastructure, could feel targeted by these systems as objects of robbery or vandalism. This phenomenon is particularly evident in solar street lighting systems, which act as an indicator of state investment in better-off, well-served districts, making economically disadvantaged, informal neighbourhoods more vulnerable to

infrastructural theft and vandalism. The lack of adequate economic resources, combined with the exclusion of local communities in the maintenance of the infrastructure, creates an environment where the inhabitants have negligible incentives to preserve or maintain the utilities they depend on (Brear & Tsotetsi, 2022; Tyhotyholo & Ncube, 2023). As a result, there is a lack of ownership and a lack of confidence in the municipal authorities, which affects the functioning of the infrastructure systems.

Governance quality in developing countries significantly determines infrastructure resilience. In South African metros specifically, bureaucratic inefficiencies render effective infrastructure management difficult. Municipal departments struggle with co-ordinating anti-vandalism responses, enforcing protection regulations, and overcoming procurement delays, contributing to their failure to prevent or respond to infrastructure vandalism. Municipal engineers and urban officers in Johannesburg have complained that they face difficulties in repairing broken solar street lights due to bureaucracy and a lack of resources (Mottiar, 2025). Poor governance leaves the community vulnerable to theft and fails to mandate the community to contribute by making them feel that they lack a say in the decision-making processes that relate to them (Van Koppen et al., 2024; Zawdie & Murray, 2013).

Climate change poses significant threats to infrastructure through extreme weather events such as flooding and heat waves. In rapidly urbanising metros like Johannesburg and Tshwane, dense development amplifies vulnerability to extreme weather events such as flooding and storms, increasing infrastructure exposure. Solar infrastructure proves particularly sensitive to weather-related disruptions, necessitating designs that integrate both technical resilience and social adaptation strategies. However, even climate-adapted

infrastructure remains vulnerable to environmental stressors and sociopolitical instability (Chang et al., 2021; Kim et al., 2022).

Finally, political and social instability compound infrastructure vulnerability, often as direct consequences of the public administrative inefficiencies discussed above. In contexts with high social inequity and political marginalisation, like South Africa, poor service delivery and governance failures generate community frustration that manifests through protest vandalism. Infrastructure destruction becomes a visible outlet for political grievances, particularly in areas experiencing repeated service delivery protests where street light vandalism serves as a tangible expression of anger toward the government (Mottiar, 2025; BTI, 2024). Consequently, infrastructure vulnerability cannot be viewed simply as a technical phenomenon but must be understood within broader sociopolitical dynamics where administrative failures create conditions for protest-driven destruction. The deliberate targeting of government infrastructure projects reflects deeper governance crises and systemic institutional breakdown.

2.4 Vandalism in Public Infrastructure: Causes, Forms, and Impacts

While Section 2.3 examined broad structural vulnerabilities in developing country infrastructure (governance failures, climate impacts, political instability), this section focuses specifically on the socioeconomic mechanisms that drive infrastructure vandalism in resource-constrained contexts.

Infrastructure vandalism is among the most significant problems in developing urban environments since it poses a serious threat to the quality and sustainability of the services of the population. The causes of vandalism may be multifactorial in most cases; they include socioeconomic disparities, bad governance, and the absence of community interaction. The lack of essential services, high unemployment rates, and economic imbalances in the majority of developing countries, including South Africa, contribute to the development of a culture of viewing the state facilities as something that can be discarded, or even something the nation should complain about (Fobosi & Malima, 2025; Brear & Tsotetsi, 2022; Mottiar, 2025). This social vice, especially in underprivileged areas, might manifest itself by deliberate demolition or theft of communal facilities, including street lights, utility cables and transport facilities.

There are numerous types of vandalism in public infrastructure. Among them is theft, in which the valuable components, such as copper wires, solar panels, and batteries, are stolen and sold in the informal markets. Stealing from solar street lighting is incentivised by the high demand for materials like copper and aluminium that can be easily sold in the black market (Qhobosheane, 2023; Mottiar, 2025). The other type of vandalism is sabotage, which is often done as a political statement or protest against government policy or perceived lack of concern. The said vandalism is more organised and may cause a lasting blockage of the service since the vandalism may take a long time to repair. Also, any destruction of property, such as broken solar panels or the smashing of street lights, is common in an area with low community participation. These kinds of vandalistic activities are a pointer to larger social discomfort and a lack of possession or sense of ownership of the infrastructure in society (Van Koppen et al., 2024; Brear & Tsotetsi, 2022).

The effects of destroying the country's infrastructure are far-reaching. It generates massive financial losses to the municipalities, which must divert resources to fix and replace the damaged infrastructure. Not only does this increase the cost of operation, but it also delays the delivery of the required services, such as electricity to the people, contributing to the increase in insecurity and crime in the affected areas. Vandalism creates social distrust in local government and undermines unity in the community. When a perception of poor infrastructure is supported or neglected by the residents, the chances of the residents participating in infrastructure repair will be minimal, resulting in an unwanted cycle of vandalism and deterioration. Solar street lighting aggravates socioeconomic disparity because the marginalised communities are poorly lit, people cannot move freely, they experience security problems and have a reduced quality of life due to theft or destruction of the systems (Rodina et al., 2024; Tshabalala et al., 2025).

2.5 Solar Street Lighting in African Urban Infrastructure

Solar street lights have become one of the most practical solutions to the lighting problem in cities, particularly in developing countries in the African continent. These systems are sources of renewable energy and assist in minimising reliance on the national grid, easing energy shortages and carbon emissions. Green infrastructure initiatives in South Africa have promoted the use of solar-powered street lights in a wider scheme of achieving climate targets within the city to support improved security. They possess certain advantages over the grid-based lighting, particularly at a distance or off-grid locations, where the energy distribution is limited or unpredictable (Bibri & Krogstie, 2021). The use of solar street lights is seen as critical in enhancing cities' infrastructure resiliency by providing efficient lighting that is

energy-saving and helps sustain the environment (Bibri & Krogstie, 2021; Skosana et al., 2023; SALGA, 2021). Moreover, their adoption by municipalities is increasingly justified through the lens of energy poverty alleviation, which is a concept that addresses the need for equitable access to reliable energy use (Tshabalala et al., 2025).

International evidence confirms that technology alone cannot guarantee infrastructure resilience. Uganda's solar street lighting initiatives in Kampala and Jinja demonstrate this paradox: while projects successfully improved safety and reduced energy costs, long-term sustainability proved dependent on strong local ownership and participatory maintenance (Gillard et al., 2019). The research revealed that excluding communities from planning and maintenance decisions exposed systems to neglect and theft, creating vulnerabilities that mirror South African experiences. These findings highlight how technical success can be undermined by social disconnection, emphasising the need for integrated approaches.

However, implementing and adopting solar street lighting in African cities has numerous challenges. Solar street lights in cities like Johannesburg and Tshwane in South Africa have been vulnerable to vandalism, particularly the theft of solar panels and batteries. As a result, although such systems are commended for possessing technical and environmental benefits, social and governance problems tend to weaken resilience. The absence of community involvement in the planning, implementation and maintenance of these systems has made them susceptible to these systems. In most cases, the fact that local people are not involved in the operation of solar infrastructure causes a sense of not being related to these structures; thus, the community is less likely to actively protect them against theft and destruction (Brear & Tsotetsi, 2022; Van Koppen et al., 2024; Qhobosheane, 2023).

Despite all this, the potential of solar street lighting in eliminating urban issues such as energy availability, homeland security and climatic changes is enormous. Solar street lights are a sustainable solution to combat energy poverty in most African cities where traditional grid infrastructure fails to cover their needs or is unreliable. One such application is the use of solar street lights, which have been shown to be effective in urban settings like Kampala and Jinja in Uganda, improving the feeling of safety and reducing dependence on the national power grid (Gillard et al., 2019; Rodina et al., 2024; Tshabalala et al., 2025). However, the sustainability of such installations is not only based on the technical architecture but also on the strength of governance structures, the effective integration of local communities and the permanence of maintenance regimes needed to address theft and vandalism of the systems.

Lastly, solar street lighting is another potential aspect of sustainable urban infrastructure in Africa, especially in municipalities that are struggling with a lack of energy. Their stability, however, depends on their ability to tackle wider governance, socioeconomic issues and community engagement problems that presently make such systems susceptible. When it is done well, whereby the management engages the local communities and institutional support is apparent, solar street lighting can bring lasting positive effects to African cities (Cantelmi et al., 2021; McPhearson et al., 2022).

While sections 2.3-2.5 identified the drivers of vandalism (INPUTS), we now turn to the institutional and technical responses (PROCESS) that municipalities deploy to address these drivers (2.10).

2.6 Community Engagement and Participatory Governance

Community Involvement has been generally accepted as a pillar of strong infrastructure management. The social capital theory is a theoretical perspective that creates a good entry point in explaining why communities that exhibit greater levels of trust, cooperation, and shared norms are more successful in securing and maintaining public assets (Liu et al., 2022; Östh et al., 2018). Kiss et al. (2022) propose that the best form of citizen engagement in governance is when communities internalise a collective stewardship of resources, thus generating a context of co-production of infrastructure services. Regarding solar street lighting, this dynamic plays out in entire neighbourhoods, becoming active owners of infrastructure instead of passive recipients of service delivery (Khemakhem & Krichen, 2024).

Despite this theoretical recognition, practical implementation reveals significant gaps. Despite substantial investment, vandalism and theft persistently threaten street lighting sustainability in Gauteng. Johannesburg reports indicated approximately 30% of the city's 270000 street lights remained non-functional, primarily due to vandalism (Sibiya, 2024). While municipalities have launched technical interventions such as Johannesburg's R15million initiative for solar street lights mounted on cement poles, designed to limit copper theft exposure (Newsroom Afrika, 2025), such measures often prove insufficient. Evaluations of such interventions have predominantly focused on energy efficiency and cost-effectiveness, with limited assessment of vulnerability to vandalism, maintenance burdens, or governance co-ordination gaps (Belloni et al., 2021; Tavares et al., 2021). Moreover, such technical solutions inadequately address deeper sociopolitical dimensions, including weak enforcement, limited community engagement, and protest-related sabotage affecting public infrastructure.

This view is further strengthened by governance theory, particularly the notion of co-production of public goods. Co-production is defined as a service delivery mechanism that involves a collaboration between citizens and authorities, which combines state resources with local knowledge and monitoring capacity (Stott, 2018).

This theoretical framework shifts the conventional hierarchical model of service delivery to a model of collaborative governance by allowing local stakeholders to become involved in the design and maintenance of infrastructure. Scholars argue that if co-production processes are institutionalised within municipal structures, the infrastructure becomes more resilient, since communities identify as partners rather than as outsiders (Van Koppen et al., 2024; Rodina et al., 2024).

The socioeconomic context significantly influences both vandalism patterns and participation effectiveness. In areas like Soshanguve and similar low-income settlements across Tshwane and Johannesburg, recurring infrastructure failures exacerbate community vulnerabilities. High unemployment, endemic poverty, and thriving informal economies create conditions conducive to cable theft and illegal scrap metal trade (Lunga et al., 2025). These factors fundamentally compromise solar project viability by creating economic incentives for infrastructure destruction. The proliferation of illegal scrap metal markets provides ready channels for stolen infrastructure components, making prevention efforts particularly challenging without robust community engagement.

Contemporary scholarship emphasises that resilient infrastructure requires governance systems combining technical efficiency with social inclusivity. Inclusive governance recognises that infrastructure sustainability depends not merely on engineering capability, but

on trust, legitimacy and local ownership. In the absence of meaningful engagement, residents perceive infrastructure as externally imposed rather than community-owned, diminishing motivation for preservation and maintenance. As Kiss et al. (2022) demonstrate, infrastructure security and stewardship failures often stem from pervasive distrust toward municipal institutions, compounded by high inequality levels and frequent protests characteristic of South African local governance.

Finally, participatory models of governance are based on the normative and sustainable idea of inclusion in decision-making. Bhati and Agarwal (2021) have shown that urban infrastructure projects are less prone to vandalism and neglect if citizens are part of their planning, budgeting and other oversight processes. Participation gives legitimacy, which leads to stewardship. The importance of the social and governance dimensions mediating technical interventions is highlighted in the literature, in a way that underlines that the resilient performance of urban infrastructure cannot be disentangled from the social dimensions (Brear & Tsotetsi, 2022; Tyhotyholo & Ncube, 2023).

2.7 Empirical Evidence in the South African Context

The South African scenario is a very interesting, yet ironic, example of community involvement in urban governance. Institutionalised mechanisms like ward committees and local forums have been made with the aim of providing citizens with a voice in the management of urban affairs at a friendly price point. However, surviving empirical data prove that such structures are rather inefficient. The ward committees are plagued with chronic under-investments and lack a significant impact on the local decision-making processes at

the municipal level (Mamokhere & Meyer, 2022; Van Koppen et al., 2024; Tyhotyholo & Ncube, 2023). The committees are, therefore, symbolic as opposed to being substantive, which compromises the prospects of substantive citizen participation in the monitoring of infrastructure development projects, including solar street lighting projects.

Informal interventions, such as neighbourhood watch programmes and grassroots surveillance agencies, tend to have a more local-level effect. By way of example, vandalism can be addressed by having surveillance of the neighbourhood; the Lentegour Neighbourhood Watch Project in Cape Town is an example of how a sense of ownership of infrastructure can be instilled in residents (Badenhorst, 2024; Modise, 2023; Brear & Tsotetsi, 2022). This study, even though it is within Gauteng, shows that community-based protective measures can cross jurisdictional boundaries. These attempts are also an indicator of increased confidence and individual responsibility — something that a city organisation frequently cannot foster.

However, there are obstacles in every situation. Brear & Tsotetsi (2022) argued that community participation in the urban governments of South Africa is often tokenism, instead of real power sharing. Consultation with communities is done, but the decision-making organs largely ignore the community input. This relationship strengthens the idea of infrastructure as a state but not a common good, which prevents civic stewardship. Furthermore, the statistics of Gauteng municipalities show that socioeconomic inequalities enhance the active application of these processes: the poorer the population, the more likely it is to use infrastructure to survive (e.g. by selling copper wiring), which highlights the limitations of engagement should the structural forces not be properly handled (Fobosi & Malima, 2025; Qhobosheane, 2023; Khalil & Rubin, 2020).

2.8 Tokenism vs. True Participation

The difference between tokenistic and real participation is one of the recurring areas of focus in the collection of South African governance literature. True commitment, as postulated by NemaKanga and Mashamaite (2024), implies affording communities the power to impact decision-making abilities, resource distribution and hold them accountable. On the other hand, tokenistic participation is defined as the symbolic performance of community or ward committee meetings, with no significant involvement in the existing governance structure. Brear and Tsotetsi (2022) argued that this form of superficial engagement, which promotes the feeling of helplessness, creates cynicism and, in the long run, undermines trust between the citizens and local government.

The infrastructure resilience impacts are far-reaching. Vandalism is usually common in places where the interaction between residents is tokenistic at best; people are more likely to equate neglect and marginalisation with acceptable frustration, and thus, the wholeness of communal infrastructure would be compromised. It is precisely the fact that municipal assets are considered to belong to a state instead of a community, which makes them targets in service delivery protests (Qwatekana et al., 2021). On the other hand, it has been demonstrated that the infrastructural resilience increases when the municipalities significantly empower the citizens. Indicatively, Van Koppen et al. (2024) and Rodina et al. (2024) demonstrated that co-managed South African water infrastructure projects were less prone to vandalism and had better maintenance results. It can be applied to solar street lighting, where a shared responsibility makes the systems less vulnerable to intentional and unintentional damage.

This further demonstrates a sociopolitical mechanism of vulnerability wherein weak participation translates into infrastructural fragility.

2.9 Critical Discussion: Participation and Infrastructure Resilience

Despite the consistent emphasis on the significance of participation in the literature, the practice in South Africa shows that there has always been a disconnect between theory and practice. Participatory models have failed to lead to resilience in Gauteng due to structural, financial and political obstacles. To begin with, resource endowment limits the capacity of such municipalities to subsidise community setups substantially (Mangara & Dorasamy, 2025). Ward committees and neighbourhood projects cannot escape the under-resourced, voluntary operating mode without funding. Secondly, political characteristics (e.g. factionalism, corruption, and mistrust) diminish the legitimacy of participatory structures. Ward councillors are also perceived as political agents, not neutral community engagement facilitators, weakening trust (Hofer, 2025; BTI, 2024; AGSA, 2024).

Thirdly, participatory governance has not been systematically incorporated into the resilience strategies in South Africa. Although urban infrastructure responses are dominated by technical solutions such as tamper-resistant hardware or Internet of Things monitoring, social interventions are fringe (Aiyede, 2025; Belloni et al., 2024; Sharifi et al., 2023). Such fragmentation is very technocratic in its governance, as the issue of infrastructure is not framed in socio-technical terms, but as an engineering issue, which in fact is called a “disciplinary bias”. Consequently, participation is considered an addition instead of an essential requirement.

More importantly, this underuse of participation has lost the chance to use social capital to be resilient. Reliable reputation, common acceptable values, and collective efficacy are shown to prevent vandalism and neglect. However, in the metros of Gauteng, participatory governance is uneven and politically weak. Without true empowerment, participation can only reinforce inequality instead of reducing it (Brear & Tsotetsi, 2022; Liu et al., 2022; Östh et al., 2018).

The evidence on participation quality (2.6-2.9) reveals that authentic engagement strengthens resilience, yet implementation faces resource and co-ordination constraints. This necessitates governance adaptation (FEEDBACK), which sections 2.11-2.12 will examine.

2.10 Institutional and Technical Strategies for Resilience

Establishing resilient solar street light systems needs proper institutional frameworks, technical design, and, most importantly, the mechanisms connecting the two. This part discusses institutional strategies (policy, co-ordination, funding), technical solutions (hardware, monitoring, surveillance), the practical constraints of cost-benefit and scale, and why an integrated socio-technical strategy is needed due to existing disaggregation in practice.

2.10.1 Institutional Strategies: Policy, Co-ordination and the Reactive-Proactive Tension

Policy and governance structures fundamentally shape the transformation of the solar street lighting investments into resilient public assets. Green public procurement frameworks and interdepartmental co-ordination efforts present opportunities to embed resilience into

tendering, design, and maintenance (Erizaputri & Bechauf, 2025; Todd & McCauley, 2021). By mandating tamper-resistant specifications, lifecycle maintenance contracts, and community participation clauses, municipalities can institutionalise resilience as a procurement outcome rather than an incidental benefit.

In South Africa, policy frameworks increasingly promote sustainable and green public procurement, responding to growing demands for urban resilience development. These policies aim to integrate sustainability considerations throughout procurement processes, potentially improving infrastructure project quality and longevity. However, implementation faces significant challenges, including corruption, limited capacity, and enforcement gaps (Erizaputri & Bechauf, 2025). Corruption in procurement processes particularly undermines project quality, as contractors may cut corners or use sub-standard materials to maximise profits. Limited municipal capacity constrains effective oversight and maintenance planning, while weak enforcement allows violations to persist unpunished. These governance deficiencies directly compromise solar street lighting operational resilience by creating systemic vulnerabilities that technical solutions alone cannot address.

These challenges manifest in structural obstacles that further hamper resilient intentions. Most municipalities' limited financial capacity and weak financial status restrain their means to invest in preventative maintenance and long-term monitoring programmes (Mutumbi et al., 2024). Political and bureaucratic fragmentation — that energy, roads, safety and finance are in diverse silos — results in co-ordination failures that promote short-term solutions to long-term prevention (Todd & McCauley, 2021). AGSA (2024) reported document capacity limitations and inconsistent expenditure patterns that further challenge proactive lifecycle planning implementation. Consequently, incentives favour reactive responses (post theft or

damage) over proactive measures to strengthen design, surveillance, and community stewardship. This reactive-proactive tension reflects institutional path dependency, where short-term political incentives and crisis management override systematic preventative resilience building.

2.10.2 Technical Innovations: Design Resilience, IoT Monitoring and Surveillance

Technically, several design options can be used to minimise weakness. Sealed batteries, hardened battery cases, enhanced poles, and the reduction of exposed copper cabling are all effective measures that minimise material indications that thieves follow (Belloni et al., 2024; Skosana et al., 2023; Mourtzia et al., 2020). Design options like built-in all-in-one luminaires (battery, controller, and panel in one sealed unit) save field cabling and, therefore, risk of theft. However, while such engineering solutions enhance material resilience, their sustainability depends on institutional enforcement and community oversight mechanisms. Without social co-ownership, even the most tamper-proof designs remain vulnerable.

These gains are extended by remote monitoring and predictive maintenance technologies. IoT sensors and voltage/health monitoring can measure battery depletion, panel deterioration, physical intrusion and indicate faults to be prioritised to reduce downtimes and the overall cost of operation of the recurring vandalism (Mourtzis et al., 2020; Belloni et al., 2024). The predictive maintenance models can also be used to prioritise the available limited resources in maintenance by replacing or repairing only the units that have already exhibited signs of failure, enhancing efficiency (Mourtzis et al., 2020). Yet, Kim et al. (2022) and Sharifi et al. (2023) note, such digitisation must be embedded within responsive governance systems; otherwise, monitoring produces data without accountability.

The use of integrated surveillance (CCTV on light poles) and motion-triggered systems may serve as a deterrent, but they have trade-offs. Surveillance, which also heightens privacy and legal and operational concerns, including who monitors feeds, data storage, and potential misuse (Brayne et al., 2023), augments the possible deterrent effect. In addition, CCTV systems need to have a stable connection, power budget, and workforce that cannot be guaranteed in underfunded municipalities (City of Tshwane, 2023; AGSA, 2024).

2.11 Challenges of Cost-Benefit and Scalability

Cost remains the central constraint shaping solar infrastructure resilience strategies. While IoT-enabled luminaires and tamper-resistant hardware offer lifecycle savings through reduced theft and maintenance, their higher upfront capital expenditure strains municipal budgets (Belloni et al., 2024; Mutumbi et al., 2024). The City of Johannesburg's R15 million pilot of cement-pole solar lights demonstrates targeted spending on theft reduction, yet scaling remains constrained by narrow revenue bases and limited maintenance reserves (Newsroom Afrika, 2025; AGSA, 2024; City of Johannesburg, 2024). This tension between coverage and durability underpins the trade-off between spatial equity and long-term resilience.

IoT and CCTV operational costs, including data plans, back-end analytics, and monitoring personnel, place recurring budgetary strains (AGSA, 2024; SALGA, 2021). This further reflects the persistent CAPEX-OPEX mismatch, where municipalities secure capital for installation but lack recurrent budgets for monitoring and maintenance (AGSA, 2024;

Erizaputri & Bechauf, 2025; City of Tshwane, 2023; City of Johannesburg, 2024). The weakness of the value proposition of advanced hardware in most low-income wards is due to the lack of reliable local maintenance teams and competing municipal priorities (Mutumbi et al., 2024; BTI, 2024). This drives municipalities to return to less expensive solutions or abandon units without repairing them, negatively affecting the long-term argument of resilient design. Participatory maintenance schemes, as suggested by Van Koppen et al. (2024), could mitigate these recurrent cost pressures by decentralising routine care and reinforcing community ownership.

2.12 Toward Integrated Socio-technical Strategies: Why Fragmentation Fails

The existing practice in most Gauteng Metros is still fragmented: procurement and technical design are treated as engineering problems, and social and governance interventions are treated as independent objects. Such distinction overlooks interactions of dependence that are the main feature of the social-ecological-technological systems (SETS) framing: technology, institutional and community dynamics interact to create resilience outcomes (McPhearson et al., 2022). This fragmentation undermines feedback learning across technical, social, and institutional domains, thereby undermining adaptive capacity, which is the essence of resilience (Sharifi et al., 2023; Helmrich et al., 2023). According to the qualitative resilience research, socio-technical integration, which implies mixing resilient hardware, predictable maintenance financing, arranged institutional accountabilities, and community co-management, is more effective than siloed interventions (Cantelmi et al., 2021).

This would be pursued by an integrated approach, which would include:

- (a) procurement policies that incorporate lifecycle resilience requirements and maintenance funds (Erizaputri & Bechauf, 2025).
- (b) technical criteria that incorporate tamper-resistant and remotely observable design features (Belloni et al., 2024; Mourtzis et al., 2020).
- (c) formalised roles of community actors (ward committees, neighbourhood watches) in surveillance and small-scale maintenance, supported by small grants or incentives (Van Koppen et al., 2024; Brear & Tsotetsi, 2022).
- (d) clear data governance policies of any surveillance and IoT systems (Brayne et al., 2023).

The synergy of these four dimensions generates positive feedback loops, i.e. financial stability supports technical durability, which in turn strengthens community trust and institutional legitimacy. This package makes technical mitigation consistent with social ownership and institutional accountability, lessening the circumstances in which vandalism is lucrative or politically appealing. Integrating social capital and institutional accountability into design reduces the incentive structures that make vandalism rational or expressive (Liu et al., 2022; Östh et al., 2018).

2.13 Research Gaps and Conclusion

The main difference between the recent interest in infrastructure resilience among scholars and policymakers and the scholarship on solar street lighting in South Africa is striking, as it

has significant gaps. To begin with, current literature favours technical and policy-driven perspectives of resilience and gives little focus on social and communal dimensions of infrastructure governance (Sharifi et al., 2023). Secondly, despite the reported hardware improvements, e.g. tamper-proof designs, IoT-based monitoring and advanced procurement systems (Belloni et al., 2024; Erizaputri and Bechauf, 2025), the approaches are likely to move the issue of vandalism into the category of a mere technical or economic problem, overlooking the larger sociopolitical consequences, i.e. inequality, marginalisation, and lack of social capital (Liu et al., 2022). The narrow techno-economic framing overlooks how governance quality, social trust, and community ownership interact with design features to determine resilience outcomes (Rodina et al., 2024; Liu et al., 2022). This oversimplified concept of resilience produces an atomistic image of resilience that does not reflect the lived experiences of communities at risk of vandalism.

The third apparent gap is the lack of a voice for the community. Common themes in the literature suggest that citizen involvement, trust and ownership are the key antecedents of sustainable infrastructure (Kiss et al., 2022; Van Koppen et al., 2024). However, empirical research studies in South Africa indicate that engagement mechanisms, including ward committees, are tokenistic in nature (Brear & Tsotetsi, 2022; Tyhotyholo & Ncube, 2023), and the repertoires of resident and community leaders' responses to solar street lighting projects are not systematically recorded. This inadequacy highlights a weakness in the profundity of the qualitative understanding regarding the interaction between the concept of social capital, participatory governance, and the prevention of vandalism. In essence, this gap is both empirical and theoretical: empirically, there is limited qualitative evidence on how residents perceive and respond to solar infrastructure; theoretically, the intersection of social capital theory with infrastructure governance.

The fourth area of discontinuity is the disconnect between the institutional structures and community-based realities. It is a common practice in policy analyses to promote integrated models of governance; nonetheless, experience shows that institutional fragmentation, fiscal limitations, and deep-seated mistrust are the barriers to effective action (Mutumbi et al., 2024; Todd and McCauley, 2021; McPhearson et al., 2022; Helmrich et al., 2023). This persistent disconnect underscores the need for a socio-technical synthesis that captures the dynamic interplay between institutional structures, technological systems, and social engagement. This is a perspective currently absent in South African urban infrastructure literature.

These combined gaps justify this study's focus on developing a context sensitive, empirically grounded, socio-technical resilience framework that integrates community participation, governance quality, and design robustness for solar street lighting sustainability in Gauteng. Through a critical evaluation of the technical and social aspects, subsequent studies can suggest stronger methods of protecting solar street lighting against vandalism and hence guarantee the sustainability of urban areas like Gauteng in the long term.

2.13.2 Synthesis: An Integrated Socio-Technical Framework for Infrastructure Resilience

This section synthesises the literature reviewed in Chapter 2 and demonstrates how each body of evidence informs the conceptual framework introduced in Chapter 1 (Section 1.6, Figure 1). The synthesis serves three purposes: Firstly, it shows how the diverse theoretical and empirical literature converges to support an integrated socio-technical systems (SETS) approach to infrastructure resilience. Secondly, it maps specific literature review sections to

distinct framework components, making explicit the golden thread connecting theory, context, and research questions. Thirdly, it identifies critical research gaps that justify the study's focus on solar street lighting vandalism in Johannesburg and Tshwane as an integrated socio-technical system.

Table 2.1 below provides a comprehensive mapping of each Chapter 2 section to the conceptual framework, showing how the literature review systematically builds the evidence base for each framework component.

Table 2.1: Literature Review Sections Mapped to Conceptual Framework Components

Section	Literature Theme	Framework Component	RQ Link
2.2	Conceptualising infrastructure resilience	Foundation	All RQs
2.3, 2.4	Vulnerability & vandalism drivers	Input: Contextual & specific mechanisms	RQ1
2.5	Solar street lighting in African infrastructure	Input: Technology context	RQ1, RQ2
2.10	Institutional & technical strategies	Process: Responses	RQ2
2.6, 2.8, 2.9	Community engagement, tokenism & participation-resilience pathway	Process: Mediator & quality	RQ3
2.11, 2.12	Cost-benefit challenges & integrated strategies	Feedback: Constraints & integration	RQ4
2.7	Empirical evidence: South African context	Context: Grounding	All RQs
2.13	Research gaps	Justification	All RQs

Note: Framework components categorised as Foundation (theoretical base), Input (drivers/context), Process (responses/mediation), Feedback (governance integration), Context (grounding), and Justification (rationale). Combined sections share thematic alignment within framework components.

Chapter 3: Research Questions/Propositions/Hypotheses

3.1 Introduction

This chapter identifies the research questions that will guide the study on the resilience of solar street lighting infrastructure in Gauteng, with a focus on the city of Johannesburg and the Tshwane metropolitan regions, and the factors that predispose it to vandalism. The questions are derived from the synthesis of the literature in Chapter 2, which identifies gaps in academic knowledge and practical solutions to improve the functionality of solar street lighting systems. The study interrogates stakeholders' perceptions and practices regarding resilience and vulnerability with attention to the socio-technical and institutional processes involved. Guided by the socio-technical (SETS) framework set out in Chapter 2, the analysis will not treat these domains in isolation but will explore the intersections and interactions between the drivers (RQ1), strategies (RQ2), and community roles (RQ3) to comprehensively address the overarching aim of developing an integrated resilience framework (RQ4)

3.2 Research Questions

3.2.1 RQ1: What are the Key Drivers of Vandalism Affecting Solar Street Lighting in Johannesburg and Tshwane?

Justification: Some socioeconomic and institutional predispositions to vandalism of urban infrastructure are outlined in the current body of literature. Studies have found that economic deprivation, poverty, political instabilities and poor governance are significant factors that dictate the presence of vandalism within the public infrastructure (Mazele & Amoah, 2021; Ragolane & Malatji, 2024). Especially, in terms of the case of solar street lighting, theft of valuable resources such as solar panels and batteries is often driven not only by financial desperation but also by criminal opportunism. The specified research question will assist in setting and exploring these drivers within the specific environment of Johannesburg and Tshwane, where the issue of infrastructure vandalism has been rather acute. It will examine the ways in which the vulnerability of the solar street lights to vandalism is worsened by social

inequality, absence of local involvement and institutional inefficiencies. (see Chapter 2; 2.3–2.5)

3.2.2 RQ2: How Effective Are Current Institutional and Technical Strategies in Preventing Solar Infrastructure Vandalism?

Justification: Various institutional and technical efforts have been undertaken in an attempt to mitigate vandalism and increase the sustainability of solar street lighting systems. Tamper-resistant hardware has been proposed as one of the technical solutions since it is considered an effective deterrent (Vidaković & Vinko, 2023). The success of these strategies is, however, questionable. Where parts of the success are reported in certain studies, others have reported issues such as financial constraints, lack of interdepartmental cooperation, and technical difficulties. The research question attempts to evaluate the applicability of the institutional and technical approach in preventing the vandalisation of solar assets, to test the difficulties of applying the approaches and their practical outcomes in Johannesburg and Tshwane. (see Chapter 2, s2.10)

3.2.3 RQ3: How Does Community Participation Impact the Resilience of Solar Street Lighting?

Justification: The role of community participation in infrastructure resiliency has been discussed in the literature in some detail. Studies show that active involvement of local communities in the construction, execution, and upkeep of infrastructure projects enhances the probability of the locals becoming the proprietors of the assets and being in control of them, which can go a long way in reducing instances of vandalism (Mazele & Amoah, 2021; Sahle, 2019). Community involvement would result in the development of social cohesion, response to governance, and collective responsibility, thus making the solar street lighting systems a success in the long term. The research question involves researching the effects of community participation in the solar street light projects in Johannesburg and Tshwane, as far as their resilience is concerned. It establishes the effectiveness of local participation in the decision-making processes, as well as the impacts of the programmes of local initiated monitoring and maintenance on the solar street lighting systems (see Chapter 2, s2.6–2.9).

3.2.4 RQ4: What Governance Changes Can Promote Sustainable Solar Infrastructure Management in Vandalism-Prone Areas?

Justification: Good governance also plays a big role in the success of infrastructure projects, at least where the issue of vandalism and poor maintenance is concerned. The models of participatory governance and co-management, which involve the local communities, municipal governments, and other parties in the management and maintenance of the public assets, are applicable in this case, as seen in the literature (Sahle & Aregawi, 2021). However, despite the theoretical attractiveness of the models of this type, their implementation has often been hampered by bureaucratic inefficiency, insufficient funds, and suspicion between the governmental institutions and the local communities. The research question focuses on determining the potential governance reforms that can be used to improve the management of solar street light systems in locations where they can potentially be vandalised (see Chapter 2; s2.10–2.12).

3.3 Conclusion

The above research questions form the heart of the research to determine the factors that determine the resilience of the infrastructure regarding the solar street lighting system in Johannesburg and Tshwane, especially within the context of the growing vandalism. The questions are designed to understand the technical, institutional, and social dynamics of the effectiveness of solar street light systems and to determine the strategies for enhancing the resilience of these systems. The results of the current study will add to the current literature on infrastructure resilience, especially in cities where the high risk of theft and destruction of public infrastructure exists. By addressing these research questions, the study will also offer useful findings on how governance, community participation and technological innovations interact in the management of solar infrastructure.

CHAPTER 4: RESEARCH METHODOLOGY

4.1 Introduction

This study aimed to investigate the resilience of solar street lighting infrastructure in Johannesburg and Tshwane, with particular focus on vandalism drivers and the effectiveness of current mitigation strategies. Urban infrastructure resilience, particularly in developing contexts, faces multifaceted challenges including socioeconomic pressures, governance deficits, and technical vulnerabilities (Mottiar, 2025; Sibiya, 2024). Solar street lighting systems, while offering sustainable energy solutions, are particularly susceptible to vandalism driven by material value and systemic socioeconomic inequalities (Lunga et al., 2025; Tshabalala et al., 2025).

The research examined the role of community participation and governance in infrastructure sustainability, recognising that technical solutions alone are insufficient without addressing the social embeddedness of infrastructure challenges (Gillard et al., 2019; Todd & McCauley, 2021). Through comprehensive data gathering, the study probed deeper into these challenges. The qualitative research design employed in this study proved appropriate, as it provided valuable insights and allowed for in-depth exploration of stakeholder perspectives on infrastructure resilience. A qualitative, exploratory research methodology was utilised, incorporating semi-structured interviews for data collection. This approach facilitated a nuanced understanding of the challenges and opportunities stakeholders face in solar street lighting resilience, ultimately contributing to the study's objectives and findings as discussed in Chapter 5.

4.2 Choice and Purpose of Research Design

The study explored the underlying problems that municipalities and communities face in sustaining solar street lighting infrastructure by gaining insights from information-rich participants. Infrastructure resilience in urban contexts is characterised by complex interactions between technical systems, institutional arrangements, and community dynamics

(Holling, 1973; Kapucu et al., 2024). The socio-technical nature of infrastructure challenges, particularly vandalism, requires research approaches that can capture both institutional perspectives and lived experiences (Fobosi & Malima, 2025; Newsroom Afrika, 2025).

A qualitative, exploratory research method facilitated the investigation of real-life challenges, contributing to existing literature on infrastructure resilience and providing recent developments for scholars through findings derived from municipal engineers, technical implementers, and community stakeholders. The research adopted a qualitative inductive approach, which offered significant advantages in investigating and uncovering specific perceptions related to infrastructure resilience and vandalism patterns (Bonoma, 1985; Creswell, 2014). Bonoma's (1985) case study found that inductive qualitative research is effective for investigating complex problems that are often neglected in traditional theory-building and analysis. This approach allowed the researcher to probe deeply into intricate issues, providing a rich, contextual understanding that quantitative methods might miss.

Furthermore, qualitative methods enabled information sharing between scholars and practitioners, therefore providing a strong foundation for advancing knowledge in the infrastructure resilience domain. This integration of practical insights and academic rigour underscores the value of qualitative research in addressing multifaceted infrastructure challenges (Bonoma, 1985; Yin, 2016). According to Creswell (2014), the benefits of an inductive qualitative approach include the enhancement, robustness, and validity of the research findings, grounded in real-world experiences and perspectives.

The study employed the SAGE (Systematic Approach to Generating Evidence) methods for qualitative research methodology and design, which emphasised a structured approach to data collection and analysis, ensuring rigour and depth in the exploration of the research questions (Bryman, 2016; McCracken, 1988; Saunders & Lewis, 2018). The researcher focused on a selected sample of individuals from various stakeholder groups within the solar street lighting infrastructure ecosystem. Participants included municipal engineers responsible for infrastructure planning and maintenance, technical implementers from original equipment manufacturers (OEMs) with expertise in solar street lighting systems. As detailed in Section 4.10, participants were selected based on professional expertise in infrastructure

delivery, which inherently positions them as institutional mediators of community needs through their implementation of politically-mandated service delivery priorities.

The research concentrated on institutional and technical strategies for infrastructure protection, community participation as a means of enhancing resilience, and governance mechanisms that either enable or constrain sustainable infrastructure management (Mangara & Dorasamy, 2025). A descriptive-explanatory research design was adopted to describe the current state of solar street lighting sustainability and identify the underlying factors influencing vandalism and resilience (Saunders & Lewis, 2018). The descriptive research design provided an accurate and systematic account of the phenomena under investigation, while the explanatory research assisted in identifying the causal effects contributing to infrastructure vulnerability and the conditions enabling sustainability.

4.3 Philosophy

The research implemented an interpretivism philosophy that posits reality as socially constructed and subjective; this approach was well-suited for the study as it allowed for the exploration of the complex and nuanced experiences of stakeholders in managing and protecting solar street lighting infrastructure, which varied widely across different contexts (Bryman, 2016; Saunders et al., 2019). Infrastructure resilience is not merely a technical attribute but emerges from social practices, institutional cultures, and community relationships that shape how systems respond to shocks and stresses (Mayar et al., 2022; Sharifi et al., 2023).

Interpretivism recognises that stakeholders construct different meanings around infrastructure challenges based on their roles, experiences, and contextual positioning. Municipal engineers may perceive vandalism primarily as a technical and financial problem, while community members may understand it as symptomatic of broader socioeconomic exclusion (Stott, 2018; Mutumbi et al., 2024). Understanding these multiple constructions of reality was essential for developing comprehensive insights into infrastructure resilience. Furthermore, interpretivism integrated human interest into the study, as real-life problems were investigated and compared with the literature, as evidenced in Chapter 6.

4.4 Approach Selection

The research opted for an inductive methodology, enabling the derivation of fresh insights and theories from the gathered data, as opposed to validating existing theories, as suggested by Saunders and Lewis (2018). While the literature on infrastructure resilience, community participation, and urban vandalism provided theoretical sensitisation (Gillard et al., 2019; Todd & McCauley, 2021), the specific dynamics of solar street lighting resilience in South African metropolitan contexts remained under-researched, necessitating an exploratory, theory-building approach.

Three methodologies were considered: (1) Deduction, where a theoretical proposition is tested through a research strategy aimed at confirming or refuting the proposition based on empirical evidence; (2) Induction, which involves constructing a theory from empirical observations to generate fresh insights and understandings for explaining phenomena; and (3) Abduction, which combines elements of both deduction and induction. An inductive approach was deemed the most suitable for this study, with a focus on fresh insights into infrastructure resilience that could extend existing theoretical frameworks such as socio-technical systems theory and urban infrastructure governance models (Bibri & Krogstie, 2021; Liu et al., 2022).

4.5 Methodological Choices

The research methodology used was qualitative, which provided for a more comprehensive understanding of the research problem (Saunders & Lewis, 2018). It allowed for an in-depth exploration of stakeholders' experiences and perspectives regarding solar street lighting resilience and vandalism. Given that infrastructure challenges in developing contexts are deeply embedded in social, economic, and governance contexts, qualitative methods were essential for capturing the contextual complexity that quantitative surveys would overlook (Fobosi & Malima, 2025).

McCracken (1988) highlights the importance of qualitative research for its ability to uncover deep, nuanced insights into cultural categories and assumptions. The socioeconomic drivers of vandalism, institutional co-ordination challenges, and community participation dynamics all require interpretive understanding that emerges through dialogue and narrative rather than numerical measurement (Tshabalala et al., 2025). Furthermore, infrastructure resilience scholarship increasingly recognises the value of qualitative inquiry for understanding adaptive capacity, stakeholder relationships, and governance processes (Kapucu et al., 2024; Sharifi et al., 2023).

4.6 Strategy

The study collected data through 13 interviews, as detailed in Section 4.10. The interview guide was developed based on the conceptual framework presented in Chapter 1 and the literature reviewed in Chapter 2, focusing on the four research questions addressing vandalism drivers, strategy effectiveness, community participation, and governance improvements (see Appendix A for the complete Interview Guide). The semi-structured interviews consisted of two types of questions: (1) Main questions that covered the key research themes aligned with the research objectives, ensuring they were clear, concise, neutral, non-leading, and free of jargon; and (2) Probing questions that explored the interviewees' responses in more depth to gain clarity and avoid ambiguity.

All interviews were conducted either in-person at municipal offices or virtually via Microsoft Teams and Otter for backup. This approach aligns with the principles of narrative research, a qualitative method that delves into personal stories and experiences to gain deeper insights into individuals and groups (Clandinin & Connelly, 2000). The data gathered through these semi-structured in-depth interviews with municipal engineers, technical implementers, and community stakeholders provided rich, contextual insights into their experiences. The method is further described in Bryman (2016), noting the importance of semi-structured interviews in qualitative research for capturing detailed and nuanced data.

4.7 Time Horizon

The research employed a cross-sectional time horizon for primary data collection, collecting interview data at a specific moment to gain the most recent insights (Bryman, 2016). Data collection was conducted over a period of two months, specifically between September and October 2025, in accordance with the researcher's schedule and participant availability. A cross-sectional technique was adopted for this study (Saunders & Lewis, 2018), which is particularly effective for capturing a snapshot of current phenomena and providing timely insights into the research questions.

The timing of data collection was relevant given the escalating challenges of infrastructure vandalism in both Johannesburg and Tshwane during this period (Newsroom Afrika, 2025; Sibiya, 2024). Furthermore, the researcher received ethical clearance from the University of Pretoria (GIBS) Ethical Clearance Committee prior to data collection. The approval process involved a thorough review of the study's methodology, including the informed consent process, data confidentiality measures, and the protection of participants' rights.

4.8 Population

The population for this study comprised stakeholders directly involved in or affected by solar street lighting infrastructure in the Cities of Johannesburg and Tshwane. These metropolitan municipalities were selected because they represent contexts with extensive solar street lighting deployment, high rates of infrastructure vandalism, and diverse governance approaches to infrastructure management (Lunga et al., 2025; Tshabalala et al., 2025). Both cities have invested significantly in renewable energy infrastructure while simultaneously experiencing severe vandalism challenges that threaten sustainability.

Due to time constraints and the qualitative nature of the study, accessing the entire population was not feasible, so a purposive sample of participants from each stakeholder category was selected. This research used sample data, which is a subgroup of the whole population (Saunders & Lewis, 2018). The population included municipal engineers responsible for

infrastructure planning, implementation, and maintenance; technical implementers from original equipment manufacturers (OEMs) with expertise in solar street lighting systems; and community stakeholders with direct expertise with public lighting, including solar street lighting systems. Participants were selected based on professional expertise rather than community representativeness. However, their professional roles inherently connect them to community needs, as they implement infrastructure decisions shaped by political mandates responding to community demands (as detailed in Section 4.10.1)

4.9 Unit of Analysis

The unit of analysis for this study was the individual stakeholder within the solar street lighting infrastructure system. Each participant was analysed as an informant providing unique perspectives based on their role, experience, and contextual positioning within the infrastructure ecosystem. The analytical process involved establishing meaningful categories, selecting appropriate data units, and associating relevant categories with the data units (Saunders & Lewis, 2018; Chenail, 2012).

This individual-level analysis was appropriate because the research questions focused on perceptions, experiences, and interpretations regarding infrastructure resilience and vandalism. Understanding how different stakeholders construct meaning around infrastructure challenges, institutional responses, and community participation required attention to individual narratives rather than aggregate organisational or community-level data (Creswell, 2014; Yin, 2018). The analytical approach recognised that infrastructure resilience emerges from the interactions and practices of diverse actors operating at different levels of the system (Holling, 1973; Kapucu et al., 2024).

4.10 Sampling Method and Size

4.10.1 Sampling Method and Criteria

A purposeful sampling method, commonly used in qualitative research, was employed, selecting participants based on their industry knowledge and experiences (Patton, 2002; Saunders & Lewis, 2018). Purposive sampling was necessary because the study required participants with specific expertise: direct involvement in solar street lighting programmes through professional roles in municipal engineering or technical implementation. The sampling strategy aimed to achieve information richness from those with intimate knowledge of infrastructure planning, implementation challenges, vandalism patterns, and community dynamics, consistent with the interpretivist paradigm and exploratory research design.

Participants included 13 professional stakeholders from the solar street lighting infrastructure ecosystem in Johannesburg and Tshwane: 9 municipal engineers and 4 OEM technical implementers. Selection criteria required:

- Municipal engineers: Minimum 5 years of relevant experience in infrastructure planning, maintenance, or project management roles, with direct involvement in solar street lighting programmes.
- OEM technical implementers: Minimum 5 years of demonstrated expertise in solar street lighting systems and experience working with metropolitan municipalities.

The professional focus of the sample reflects the institutional structure through which community concerns are translated into infrastructure responses. Municipal engineers operate as the implementing arm of political mandates, executing directives shaped by community demands expressed through ward meetings, service complaints, and political pressure on elected officials. Their professional decisions regarding technology choices, site prioritisation, and mitigation strategies respond to specifications and priorities ultimately driven by community needs as articulated through political processes. Similarly, OEM technical implementers design and deliver solutions according to municipal procurement requirements, which are themselves shaped by political imperatives to address community infrastructure challenges. As such, while the study does not include direct community voices, participants' professional practice is fundamentally oriented toward addressing community needs as mediated through institutional and political structures.

This sampling approach was strategically aligned with the research questions, which required an in-depth understanding of vandalism drivers, technical mitigation strategies, institutional responses, and governance frameworks. These questions necessitated expertise from those directly responsible for infrastructure planning, implementation, and response to community

concerns. While participants were interviewed in their professional capacities, all remained embedded in their own communities as residents, voters, and neighbours, experiencing infrastructure challenges beyond their organisational roles. However, it should be noted that the study did not include residents without professional involvement in infrastructure, such as ward committee members, community forum representatives, or residents from informal settlements. This limitation is acknowledged in Section 7.4.

4.10.2 Sample Composition

Figure 4.1 below presents the demographic profile of participants who were interviewed for this study:

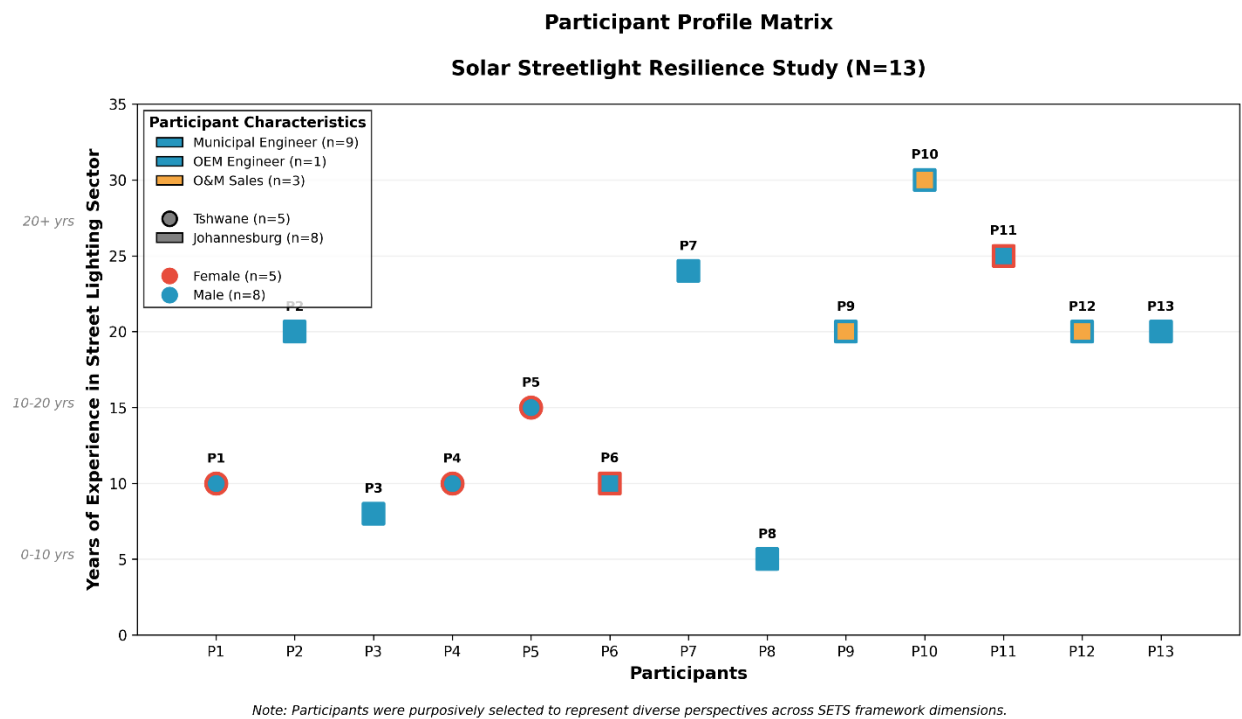


Figure 4.1: Participant demographic profile

The final sample comprised 13 participants distributed across Johannesburg (eight participants) and Tshwane (five participants). Municipal engineers represented the largest category (nine participants), reflecting their central role in infrastructure planning, implementation, and maintenance. OEM technical staff comprised four participants, providing

perspectives on technical design, implementation challenges, and market dynamics. The sample included five female and eight male participants, with experience ranging from 5 to 30 years in public lighting or municipal infrastructure management.

Municipal engineer participants held diverse roles spanning project management, electrical engineering, regional operations, and strategic planning, ensuring representation across different operational levels and functional areas. This diversity enabled the study to capture perspectives from both frontline practitioners managing day-to-day vandalism responses and senior decision makers shaping policy and procurement frameworks. OEM participants similarly represented varied organisational roles, including technical design, field implementation, and client relationship management, providing insights into how supplier organisations adapt their products and services to meet municipal specifications driven by community infrastructure needs.

4.10.3 Sample Size and Data Saturation

The researcher systematically tracked code emergence across the 13 interviews using Excel, documenting which interview each new code first appeared in and monitoring cumulative code development (see Appendix D, Saturation Grid). This tracking revealed a clear saturation pattern:

- Interview 1: 18 codes emerged, establishing the core analytical framework
- Interviews 2-3: 10 additional codes emerged (5 each), bringing the total to 28 codes
- Interviews 4-5: No new codes emerged
- Interviews 6-7: 2 final codes emerged, completing the 30-code framework
- Interviews 8-13: No new codes emerged, confirming saturation

The last new code appeared at interview 7, with the subsequent six interviews serving to validate the coding framework, elaborate on existing themes, and ensure no major analytical categories had been overlooked. This pattern demonstrates clear thematic saturation, consistent with Guest et al. (2006), who found that thematic saturation typically occurs within 12 interviews and often earlier. The six post-saturation interviews (8-13) provided confidence that the analytical framework was comprehensive and stable.

Figure 4.2 below illustrates this saturation pattern. The graph demonstrates that code emergence declined sharply after the initial three interviews (which generated 28 of the 30 codes), with the final two codes appearing at interviews 6 and 7. The six subsequent interviews (8-13) generated no new codes, confirming framework stability. This pattern provides empirical evidence that data collection continued well beyond the point of saturation, ensuring comprehensive thematic coverage.

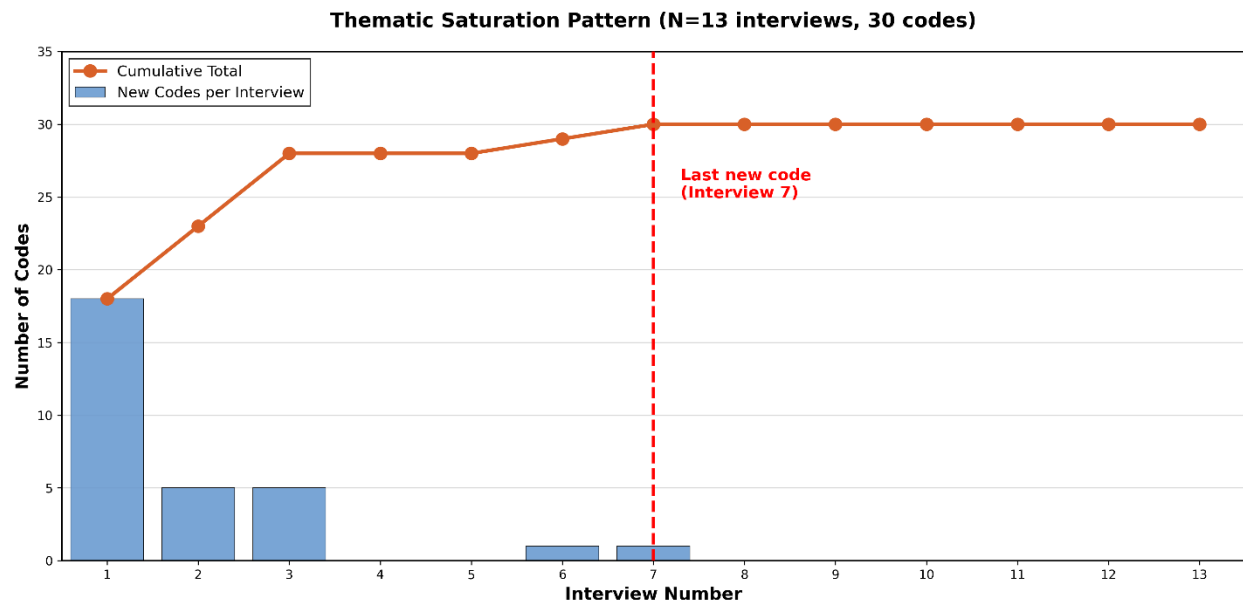


Figure 4.2: Thematic saturation pattern showing code emergence across 13 interviews

The sample composition (municipal engineers from different operational levels and OEM implementers from varied organisational roles) required continuing data collection beyond the point where new codes ceased emerging to ensure adequate representation across different professional positions and organisational contexts. While no new codes emerged after interview 7, later interviews provided valuable elaboration, contextual depth, and validation of patterns identified in earlier interviews.

The final analytical framework comprised **30 codes** organised into five parent categories: Vandalism Drivers (9 codes, 31.9% of coded segments), Technical Responses (5 codes, 25.9%), Institutional Responses (3 codes), Community Participation (7 codes, 21.4%), and Governance Changes (6 codes, 20.8%). Complete code definitions, parent code

classifications, decision rules, groundedness metrics, and saturation tracking are provided in Appendix D.

4.11 Measurement Instrument

The interview guide, developed based on the conceptual framework and literature review, served as the primary measurement instrument (see Appendix A). Saunders and Lewis (2018) suggest that common qualitative research tools include interviews, questionnaires, observations, documents, and video conferencing. Qualitative data collection was conducted through semi-structured interviews, allowing respondents to express their opinions in their own words while ensuring coverage of key themes related to vandalism drivers, strategy effectiveness, community participation, and governance improvements (Bryman, 2016; McCracken, 1988). In addition to tracking the number of text segments coded (groundedness), the researcher documented which participant transcripts contained each theme to assess pattern prevalence across the sample.

The interview guide was organised around the four research questions, with questions designed to elicit perspectives on socioeconomic drivers of vandalism (Lunga et al., 2025; Stott, 2018), institutional and technical strategies (Khemakhem & Krichen, 2024; Mourtzis et al., 2020), community participation mechanisms (Gillard et al., 2019; Todd & McCauley, 2021), and governance arrangements (Mangara & Dorasamy, 2025).

The interview guide incorporated three question types following established qualitative research design principles: (1) Grand tour questions to establish context and build rapport (e.g. 'Can you tell me about your role in solar street lighting?'); (2) Main questions aligned with each research question to explore key themes systematically; and (3) Follow-up probing

questions to elicit deeper insights and clarification, particularly when participants provided brief responses or required encouragement to elaborate on their experiences.

Microsoft Teams and a hand-held recording device were chosen as the data gathering platform for virtual interviews, supplemented by in-person interviews conducted at municipal offices.

The interview guide underwent rigorous pilot testing to ensure question clarity, relevance, and capacity to elicit rich responses. The pilot testing process followed a two-stage approach recommended in qualitative methodology literature. In the initial stage, the researcher conducted a practice interview with a family member who has professional experience in infrastructure management. This internal pilot revealed that several questions were too abstract and required reformulation to be more concrete and accessible. The researcher noted that questions phrasing needed adjustment to reduce ambiguity and ensure participants could readily connect questions to their lived experiences.

Based on insights from this preliminary pilot, the researcher refined the interview guide by: (1) rephrasing abstract questions to use more concrete, experience-based language; (2) resequencing questions to improve conversational flow; (3) shortening overly complex questions into simpler components; and (4) developing a set of supplementary probing questions to deploy strategically with less talkative or emotive participants. These probing questions served as conversational scaffolds to help participants elaborate on their experiences and ‘come out of their box,’ as it were, particularly when initial responses were brief or surface-level.

Following these refinements, the researcher conducted a second pilot interview with an infrastructure professional to test the revised guide. This second pilot confirmed that the questions were now clearer, more accessible, and better positioned to elicit detailed responses. The iterative pilot testing process strengthened the measurement instrument’s validity and reliability, ensuring it could effectively capture the nuanced perspectives necessary for addressing the research questions.

4.12 Data Gathering Process

The structured data collection process followed established qualitative research procedures grounded in the works of Creswell (2014), Patton (2002), McCracken (1988), Bryman (2016), and Lincoln and Guba (1985), with additional ethical and technical practices aligned with Davidson (2009), Halcomb & Davidson (2006), and Saunders et al. (2019).

4.12.1 Primary Data Collection: Semi-Structured Interviews

Primary data were collected through semi-structured interviews conducted between September and October 2025. The interview process was organised into three distinct phases:

Step 1: Ethical Approval and Recruitment. Ethical clearance was obtained from the University of Pretoria (GIBS) Ethical Clearance Committee prior to any participant contact. Participants were identified and recruited through professional networks, municipal contacts, and community organisation referrals.

Step 2: Scheduling and Pre-Interview Preparation. Interviews were scheduled at times and locations convenient for participants. The researcher sent invitation emails that included a brief introduction to the research topic and purpose, along with the interview questions participants would be asked. This advance sharing of questions allowed participants to prepare and reflect on their experiences, enhancing the depth and quality of responses during the actual interview.

Step 3: Information Sheet and Consent. Prior to each interview, participants were provided with an information sheet explaining the research purpose, the voluntary nature of participation, confidentiality protections, and their right to withdraw. Written informed consent was obtained from all participants (see Appendix B for the Informed Consent Form).

Step 4: Interview Conduct. Each interview followed a structured four-stage approach: (Stage 1) Opening and rapport building: The researcher thanked the participant for their

participation and reviewed ethical protocols, explicitly informing participants that they were not obligated to answer questions they felt uncomfortable with or that might compromise them professionally. (Stage 2) Contextual introduction: The researcher asked participants to introduce themselves and describe their professional relationship to solar street lighting infrastructure, including their role, responsibilities, and length of experience in this domain. This contextual grounding helped both the researcher and participant establish a shared understanding. (Stage 3) Core research questions: The researcher systematically worked through the interview guide questions, allowing participants to respond in their own words while occasionally deploying probing questions to encourage elaboration or clarification. (Stage 4) Closing: The researcher thanked participants, invited any final comments or questions, and explained the next steps regarding transcript verification.

Step 5: Recording and Documentation. All interviews were audio-recorded with participant permission. For all interviews, Microsoft Teams recording functionality was utilised, and a digital voice recorder by way of phone was used. The researcher also took detailed notes during interviews to capture non-verbal cues, contextual observations, and preliminary analytical insights that emerged during the conversation.

Step 6: Translation and Transcription. The interviews were conducted in English, the primary business language of South Africa. Each interview lasted approximately 30 to 60 minutes, allowing sufficient time to explore each research question in depth while respecting participants' time constraints. All 13 interviews were transcribed using Microsoft Teams recording functionality, supplemented by Otter.ai transcription software. Given that automated transcription tools struggle with South African English accents, the researcher employed DeepSeek artificial intelligence to synthesise outputs from both platforms and generate cleaned transcripts.

Given that we struggled with automated transcription tools, we were therefore uncertain which platform would perform better. The researcher employed a triple-redundancy recording strategy. Each interview was simultaneously recorded on: (1) the researcher's personal phone, (2) Microsoft Teams with auto-transcription enabled, and (3) Otter.ai for backup transcription. Following data collection, the researcher fed both the Microsoft Teams and Otter.ai transcripts, along with the audio recording, into DeepSeek AI with instructions to

synthesise the best elements of both transcripts, reconciling discrepancies and selecting the most accurate rendering of participant speech. The researcher then meticulously reviewed the AI-consolidated transcript while listening to the phone audio recording, manually correcting any remaining inaccuracies or misinterpretations. This rigorous multi-stage verification process ensured transcript accuracy despite the challenges posed by South African English phonology.

Following researcher verification, the refined transcript was sent back to some participants for member checking. This step ensured that the transcript represented a true and accurate reflection of what was discussed during the interview, allowing participants to identify any misinterpretations or request clarifications. This member checking process enhanced the credibility and trustworthiness of the data.

Step 7: Secure Storage. Recordings were stored securely on encrypted, password-protected devices, then all other existing copies were deleted.

4.12.2. Secondary Data Collection: Documentary Review

In addition to primary interview data, the study utilised publicly available secondary documents for triangulation and contextualisation. These included municipal infrastructure reports, Auditor-General of South Africa (AGSA) audit reports, policy documents on renewable energy infrastructure, and publicly accessible municipal council or related organisation minutes and reports related to street lighting and infrastructure projects.

Selection criteria for documentary data included: (1) relevance to solar street lighting infrastructure in Johannesburg and Tshwane; (2) publication or availability within the past five years (2021-2025); (3) official status as municipal, provincial, or national government documents; and (4) public accessibility without requiring confidential access.

Documentary data were used to corroborate interview findings, provide contextual background on policy and governance frameworks, and triangulate participant accounts of institutional challenges and responses.

4.13 Analysis Approach

The data analysis followed Braun and Clarke's (2006) thematic analysis framework. The approach was primarily inductive, allowing themes to emerge from the data, with limited deductive sensitisation from the SETS framework and resilience theory concepts established in the literature review (Holling, 1973). This enabled openness to unanticipated patterns while remaining attentive to theoretical concepts from the infrastructure resilience literature.

Interview recordings were transcribed and verified for accuracy. A sample of transcripts was returned to participants for member checking. Verified transcripts underwent systematic coding using Excel to organise and manage the analytical process. The researcher developed an iterative codebook documenting code names, definitions, decision rules, and groundedness metrics (see Appendix D). Throughout the analysis, a reflexive journal captured analytical decisions, emerging patterns, and methodological reflections.

The analysis proceeded through standard thematic analysis phases: familiarisation with transcripts, initial coding of data segments, organisation of codes into parent categories (Vandalism Drivers, Technical Responses, Institutional Responses, Community Participation, Governance Changes), theme development within categories, and review of themes against coded data. An audit trail was maintained, including dated analytical memos, version-controlled coding schemes, and documentation of code emergence, supporting the dependability and confirmability of findings.

The analysis operated at two levels: descriptive (systematically documenting participant accounts) and interpretive (examining underlying patterns, tensions, and relationships between themes). For example, codes related to community participation were examined not only for what participants reported about participation mechanisms, but also for what these accounts revealed about power dynamics and gaps between policy intentions and implementation realities.

The findings were organised to address each research question systematically, as presented in Chapter 5. Within each section, themes are illustrated with direct quotations from participants to ground the analysis in their accounts.

4.14 Ethical Considerations

The research adhered to rigorous ethical standards throughout the study. Ethical clearance was obtained from the University of Pretoria (GIBS) Ethical Clearance Committee prior to any data collection activities. All participants provided written informed consent after receiving detailed information about the study's purpose, procedures, risks, benefits, and their rights as research participants (see Appendix B).

Participant anonymity was maintained throughout the study using pseudonyms in all reporting and dissemination of findings. No personally identifiable information appears in the research outputs. Participants were informed of their right to withdraw from the study at any time without penalty, and of their right to decline to answer any specific questions during the interviews.

Consistent with ethical clearance requirements, all de-identified data will be stored in an encrypted digital archive with restricted access (limited to the researcher and research supervisor) for a minimum of 10 years, as required by the university's research data management policy. The re-identification key linking pseudonyms to participant identities is stored separately from the data in a password-protected file accessible only to the principal researcher. Where the researcher used contracted services, they signed the study's POPIA-compliant Non-Disclosure Agreement (Appendix C) prior to receiving any audio files or data, ensuring confidentiality and compliance with South Africa's Protection of Personal Information Act.

Given the dual roles of many participants as both municipal employees and community residents, particular care was taken to create a safe interview environment where participants could speak freely without fear of professional repercussions. Interviews were conducted in private settings, and participants were assured that their employers would not be provided with individual response data.

4.15 Quality Controls

Quality control was a crucial aspect of the qualitative research methodology, ensuring the accuracy, reliability, and credibility of the research findings. The study employed multiple strategies to enhance trustworthiness, following Lincoln and Guba's (1985) criteria of credibility, transferability, dependability, and confirmability.

Credibility was enhanced through triangulation and member checking. Triangulation involved using multiple data sources (municipal engineers and OEM technical staff from different organisational levels and functional roles, and comparing different perspectives to validate the information provided (Turner et al., 2017; Patton, 2002). Data source triangulation was particularly valuable given that infrastructure resilience involves multiple actors with potentially divergent perspectives and interests (Mayar et al., 2022; Mutumbi et al., 2024). Additionally, publicly available documentary data from municipal reports and AGSA audits were used to corroborate interview findings where possible. Member checking involved returning a one-page summary of preliminary key themes to a subset of five participants to verify interpretations and ensure accuracy. This approach allowed participants to confirm that the researcher accurately understood their experiences, perspectives, and responses, thereby improving the reliability and validity of the findings.

Transferability was facilitated through thick description of the research context, participant characteristics, and institutional settings. Detailed descriptions enable readers to assess the applicability of findings to their own contexts. The findings are contextualised within the broader literature on urban infrastructure challenges in developing contexts (Fobosi & Malima, 2025; Mottiar, 2025), enabling readers to determine the relevance of insights to their specific settings.

Dependability and Confirmability were supported through maintenance of a comprehensive audit trail, reflexive journal entries documenting researcher perspectives and decisions, and an evolving codebook. Regular peer debriefing sessions with the research supervisor and fellow GIBS colleagues provided external checks on the analytical process, challenging assumptions and interrogating emergent interpretations. The audit trail allows

external reviewers to trace the research process and verify the logical links between data and conclusions.

4.16 Limitations

Understanding and addressing the limitations of qualitative research methods can significantly enhance the reliability and validity of findings. The primary limitations of this study included potential for biases and subjectivity in data collection, analysis, and interpretation (Bryman, 2016; Creswell et al., 2014).

Sample Size and Generalisability: The qualitative research involved a sample of 13 participants, including municipal engineers and OEM implementation staff, within the solar street lighting infrastructure ecosystem in Johannesburg and Tshwane. This limited sample size influences the generalisability of the findings. While the sample provided rich, contextual insights appropriate for qualitative inquiry, findings cannot be statistically generalised to all South African municipalities or all solar street lighting contexts. The focus on two metropolitan municipalities in Gauteng province means that findings may not be directly transferable to rural municipalities or provinces with significantly different socioeconomic conditions, governance structures, or infrastructure challenges.

Time Constraints: The data collection process faced some scheduling delays due to participant availability. The researcher relied on available networks to secure interviews, particularly with municipal officials and technical experts, which necessitated accommodating their schedules. Conducting qualitative research is inherently time and resource-intensive, requiring significant investment in data collection, analysis, and interpretation (Saunders & Lewis, 2018; Turner et al., 2017).

Cross-Sectional Design: The cross-sectional nature of the study means that data represent a snapshot at a particular moment (September to mid-October 2025). Infrastructure resilience and vandalism patterns may evolve over time in response to policy changes, economic shifts, or community interventions. Longitudinal research would provide deeper insights into

temporal dynamics and the long-term effectiveness of resilience strategies (Jebb & Tay, 2016).

Researcher Positionality: The researcher's background and experience in street lighting may have influenced question framing, data interpretation, and theme identification. While reflexivity practices were employed to acknowledge and bracket these biases, complete objectivity is neither possible nor desirable in interpretivist research. Transparency about the researcher's positionality allows readers to assess potential influences on findings.

Social Desirability Bias: Participants, particularly municipal officials interviewed in professional capacities, may have responded in socially desirable ways, emphasising successes and downplaying failures or governance shortcomings. While efforts were made to create a non-judgemental interview environment and ensure confidentiality, this bias cannot be entirely eliminated (Jordan & Troth, 2019). Triangulation across stakeholder groups and with documentary sources helped mitigate this limitation by providing multiple perspectives on the same phenomena (to be discussed under section 6.2).

Chapter 5: Findings and Results

5.1 Introduction

This chapter presents findings from 13 semi-structured interviews with municipal engineers and OEM professionals managing solar street lighting infrastructure in Johannesburg and Tshwane. Analysis reveals vandalism as a systemic vulnerability rather than isolated criminality. Findings are organised around four research questions, each corresponding to a component of the SETS framework (Chapter 1, Section 1.6): Input drivers of vulnerability, Institutional and Technical Response mechanisms, Mediating community participation dynamics, and required governance arrangements.

The chapter begins with an overview of the analytical framework (Section 5.2), followed by thematic findings organised by research question (Sections 5.3-5.6). Each section uses participant quotations to illustrate themes and patterns. Section 5.7 synthesises cross-cutting findings and transitions to Chapter 6.

5.2 Analytical Framework Overview

As detailed in Section 4.10, this analysis draws on interviews with 13 participants whose professional roles and experiences are described in Chapter 4. Individual participant characteristics, including years of experience, organisational affiliation, and metro location, are provided in Appendix E for reference throughout this chapter.

The 30 codes developed through thematic analysis were organised into five parent categories that structure the presentation of findings. Table 5.1 below summarises the distribution of codes and analytical effort across the four research questions. Complete code definitions, groundedness metrics, and saturation tracking are provided in Appendix D.

Table 5.1: Coding Framework Summary

Research Question	Parent Code Categories	Code Count	Groundedness
RQ1: What are the key drivers of vandalism affecting solar street lighting in Johannesburg and Tshwane?	Vandalism Drivers	9 codes	323 segments (31.9%)
RQ2: How effective are current institutional and technical strategies in preventing solar infrastructure vandalism?	Technical Responses Institutional Responses	8 codes	262 segments (25.9%)
RQ3: How does community participation impact the resilience of solar street lighting?	Community Participation	7 codes	217 segments (21.4%)
RQ4: What governance changes are needed to enhance infrastructure resilience?	Governance Changes	6 codes	211 segments (20.8%)
Total	5 parent categories	30 codes	1,013 segments

The analytical framework reflects the interconnected nature of infrastructure vulnerability. While codes are organised by research question for clarity, many themes inform multiple aspects of resilience. For instance, weak enforcement appears both as an institutional response challenge and as a factor enabling community disengagement. This interconnection

reinforces the need for integrated rather than siloed interventions, a theme that emerges consistently across all four research questions.

5.3 Drivers of Vandalism: Infrastructure under Systemic Stress

Research Question 1: What are the key drivers of vandalism affecting solar street lighting in Johannesburg and Tshwane?

Participant narratives reveal vandalism not as isolated criminal acts but as systemic dysfunction spanning economic, spatial, social, and institutional dimensions. Five interconnected driver categories emerged (see Table 5.3): economic value and resale markets; locational vulnerability structures; crime concealment through social disengagement; insider exploitation of institutional knowledge; and shadow market infrastructure enabling demand.

5.3.1 Economic Incentives and Material Value

Participants identified component resale value as a primary driver (all 13 participants). Analysis revealed three distinct yet overlapping motivations differentiated by actor intent and market integration.

Survival theft reflects economic desperation where infrastructure provides immediate resource access. P5 characterised this pattern: “I will be direct. Rapid urban in-migration brings many people without access to services. In the urban environment, there is no firewood option, so some resort to illegal connections. Street lighting infrastructure, especially ABC on arterial roads, becomes a target.”

P8 and P12 described similar patterns in informal settlement contexts, where theft serves immediate electricity and lighting needs rather than commercial gain. Five participants distinguished survival-motivated theft from commercial networks based on component selection (cable for illegal connections versus batteries for resale) and perpetrator profiles (residents versus external actors). This account suggests that some vandalism reflects

informal infrastructure access strategies where formal systems exclude marginalised populations, complicating enforcement responses assuming profit motivation.

Opportunistic criminality targets components with established monetisation pathways. Seven participants described perpetrators with knowledge of secondary markets systematically removing high-value elements: solar panels, batteries, and copper cabling. P2 noted: “Component visibility and accessibility increased vulnerability. Offenders see what is there and assess how easily they can remove it.” Unlike survival theft, this category involves actors outside affected communities, operating with specific resale intent.

Crisis-amplified demand emerged during load shedding periods when solar components commanded premium prices. P7 explained: “Load shedding intensified demand for batteries and solar components. When households and businesses need backup power, the secondary market thrives. Components stolen today are installed elsewhere tomorrow.”

Four participants reported theft rate increases correlating with load shedding frequency, with P11 estimating incidents occurring “two to three times more during intensive load shedding periods compared to normal conditions.” This typology reveals a policy trade-off: the same infrastructure crisis (unreliable grid electricity) that justifies solar adoption simultaneously increases vandalism risk by elevating component market value. Eight participants explicitly noted this tension, with P3 articulating: “We have installations in the inner city. Our strategy for deploying solar high-masts has two drivers: firstly, reducing theft and vandalism; secondly, lowering energy costs by reducing dependence on Eskom tariffs.”

Multiple participants emphasised that economic drivers alone cannot explain vandalism patterns (P2, P5, P8, P11, P13). Geographic, social, and institutional factors mediate how economic incentives translate into theft, suggesting that poverty alleviation, absent concurrent attention to opportunity structures and governance failures, would prove insufficient.

5.3.2 Spatial Vulnerability and Design-Created Opportunity

Vandalism demonstrates strong spatial clustering, revealing how location and design create differential vulnerability. Three spatial risk factors emerged: proximity to informal settlements and scrapyards; physical accessibility of components; and remoteness from surveillance or community oversight.

Infrastructure near informal settlements faces dual pressures, enabling illegal connections and facilitating component resale through local informal economies. P8 stated: “Location is decisive. Near informal settlements, do not use ABC cable because it gets tapped for illegal connections. In previously disadvantaged or scrap-market-proximate areas, items are stolen for resale. Remote stretches are vulnerable because offenders can act unobserved.”

Participants universally identified proximity to informal settlements or scrapyards as the primary spatial risk factor, with P5, P8, and P12 describing these locations as experiencing persistently higher vandalism rates despite technical hardening measures. This spatial pattern complicates purely technical responses: hardening components may deter opportunistic theft, but addresses neither underlying access deprivation driving illegal connections nor socioeconomic conditions enabling component markets.

Physical accessibility emerged as a design-created vulnerability. Solar systems concentrate valuable components in publicly accessible locations. Unlike grid-connected lights, where infrastructure remains hidden underground, solar systems display batteries, panels, and controllers prominently. P2 explained: “Every design decision involves trade-offs between accessibility for maintenance and exposure to theft.”

Remote locations amplify vulnerability through the absence of natural surveillance. Arterial roads and highways lack the passive community oversight that characterises residential areas. Theft occurs unwitnessed, with an extended time between commission and discovery. Several participants noted vandalism in such locations often progresses to complete system dismantling rather than component theft, as offenders face minimal interruption risk. P4

described: “In remote locations or during extended periods without patrol, even hardened measures get breached.”

Across participant accounts, installations in three contexts exhibited the highest vulnerability: within proximity to informal settlements (mentioned by nine participants), adjacent to scrapyards or informal trading areas (eight participants), and on remote arterial roads with minimal traffic (seven participants). The spatial dimension reveals infrastructure deployment following technical-planning logic (energy efficiency, coverage optimisation) while vandalism vulnerability follows socio-spatial logic (proximity to poverty, accessibility, surveillance gaps).

5.3.3 Social Fragmentation and the Fear-Knowledge Gap

Community disengagement emerged as both cause and consequence, creating self-reinforcing cycles. Three dynamics characterise this social dimension: deliberate destruction facilitating crime; fear-based non-reporting despite perpetrator identification; and passive acceptance of infrastructure loss as inevitable.

Several participants reported vandalism serving crime concealment rather than component theft. Criminals disable street lights to create darkness, enabling burglary, vehicle theft, or assault. P7 stated: “Deliberate destruction facilitates criminal activity. We see patterns where lights are disabled before house-breaking incidents. The vandalism is not about stealing components but creating conditions for other crimes.”

This instrumental vandalism reveals infrastructure as embedded within broader criminal ecosystems. When street light damage enables subsequent property crime, the economic impact multiplies beyond replacement expenses. Current municipal reporting systems rarely capture these linkages, treating infrastructure vandalism and property crime as separate phenomena.

Multiple participants confirmed communities typically know perpetrator identities yet fail to report them (P3, P7, P9, P11). P9 explained: “We have educated communities extensively, but fear and distrust limit reporting. Offenders within communities are known, yet under-

reported. A whistle-blowing hotline exists, but people worry about exposure and victimisation.” P3 elaborated on enforcement perception gaps: “There is disengagement and poor co-ordination between communities and law enforcement. Communities know who offends but fear reporting due to victimisation. Some police view this as petty crime and deprioritise it.”

5.3.3.1 Participant-Proposed Protection Mechanisms

In response to identified fear barriers, seven participants explicitly proposed protective mechanisms enabling safe reporting. P9’s observation that existing whistle-blowing hotlines remain underutilised “because people worry about exposure” implies a need for enhanced anonymity protocols. P3 stated this explicitly: “We need assurance that reporting will yield protection rather than exposure.”

Four participants (P3, P7, P9, P12) advocated for protection frameworks preceding community engagement intensification. P7 proposed: “Safety must come first. You cannot ask communities to identify criminals without the capacity to protect informants from retaliation.” P12 suggested institutional reforms: “Law enforcement response time matters. If reporting leads to immediate action within hours rather than days, retaliation risk decreases because perpetrators have less time to identify informants.”

These proposals align with community protection codes identified in thematic analysis (Appendix D: Codes “Whistleblower Safety,” “Informant Protection,” “Community Security Mechanisms”). Participants characterised protection capacity as a prerequisite rather than a concurrent objective for effective community participation in infrastructure protection.

A third dynamic emerged around passive acceptance. Repeated infrastructure failure breeds fatalism, where communities cease expecting reliable service delivery. P7 noted: “Trust and integrity in forums are essential. Where leadership strays, people disengage. Structures need clear rules, training, and accountability to avoid being captured by criminal interests.”

P7’s observation regarding criminal infiltration of CPFs suggests institutional capture, where intended protection structures serve criminal intelligence-gathering about security measures

and response times. When criminal elements infiltrate Community Policing Forums or ward committees, mechanisms intended to protect infrastructure become vectors for exploitation. Good-faith community members withdraw upon recognising that structures designed for collective benefit serve criminal interests.

5.3.4 Insider Vulnerabilities: Institutional Knowledge as Liability

Internal staff involvement represents a troubling driver, transforming institutional knowledge from asset to liability. Participants across municipal and OEM categories acknowledged insider theft as particularly damaging (9 of 13 participants). Employee knowledge of system design, security measures, and patrol schedules enables sophisticated, high-value theft that external opportunists cannot accomplish.

Two forms emerged: direct employee theft using access and expertise to steal components; and information leakage, where employees share technical details with external criminals, providing reconnaissance enabling targeted theft. P2 stated: “There is such a risk. Insider knowledge can shift offenders from opportunistic to organised crime. This reinforces the need for continuous monitoring, early warning, and response capacity.”

The shift from opportunistic to organised crime marks a qualitative escalation. Insider-enabled theft demonstrates planning, system knowledge, and co-ordination that overwhelming standard security measures. Criminals know which components have the highest value, how to disable alarms without triggering responses, and when security patrols rotate. Participants attributed insider involvement to multiple factors: low municipal salaries creating economic pressures; lack of consequences signalling institutional tolerance; and procurement corruption where vendors inflate quotes or supply sub-standard components with kickbacks. P9 described: “Poor workmanship is a key risk. Examples: leaving the inspection hole unlocked after work makes it easy to pull wires. A luminaire not properly tightened can be twisted off. Sometimes this is negligence, sometimes deliberate sabotage, creating future repair opportunities.”

P9's account illustrates blurred lines between incompetence and corruption. When workmanship failures systematically create vulnerability, distinguishing negligence from intentional sabotage becomes difficult. Five participants raised concerns that contractors deliberately compromise installations to generate maintenance contracts, representing institutional dysfunction that standard technical interventions cannot address.

5.3.5 Secondary Market Infrastructure: Demand-Side Enablers

10 of 13 participants identified functioning secondary markets for stolen components as critical yet under-addressed drivers. P11 stated: "We need an integrated strategy that targets the second-hand market to reduce demand for stolen components through stronger regulation and enforcement. Designs should be vandal-resistant, but equally important is cutting off the market where criminals monetise theft."

P7 proposed downstream intervention priority: "Harden the downstream market. Target the scrap and resale pathway for stolen materials. Offenders must be heavily punished. Deploy tracking with real response and implement trackers and alarms with contracted private security response."

Regulatory Gap Identification

Participants characterised current regulatory frameworks as creating policy asymmetries favouring criminal markets. P6 described scrapyards' accountability gaps: "Businesses must not credit items they did not sell. Return them to the customer. You do not know how they were obtained. Reporting can be complicated; many businesses avoid involvement because processes can be punitive or risky."

Five participants (P5, P6, P7, P11, P13) specified regulatory weaknesses: scrapyards' operators face minimal verification requirements when purchasing metal; no central database tracks component serial numbers, thus preventing stolen property identification; law enforcement deprioritises scrapyard monitoring, treating infrastructure theft as property crime rather than economic sabotage.

Participant-Framed Policy Asymmetry

Eight participants explicitly contrasted municipal burden with market participant impunity. P11 stated: “We bear full replacement costs while scrapyards profit with minimal legal risk.” P5 added: “Laws also need attention: our framework often favours perpetrators over victims. We need clearer criminal categories for infrastructure crime and tools like micro-dot identifiers to track components.”

These demand-side interventions were framed by participants as policy priority shifts from exclusively supply-side hardening (technical infrastructure protection) to concurrent market regulation. P7 characterised the logic: “Without buyers, stolen components lose value, eliminating theft motivation. Yet our response focuses 90% on protecting infrastructure, 10% on regulating markets. Those proportions should reverse.”

Participants’ regulatory reform proposals connect to demand-side market control codes in thematic analysis (Appendix D: Codes “Scrapyard Regulation,” “Secondary Market Control,” “Buyer Accountability”). The consistent framing across participant categories (municipal and OEM) suggests perceived policy gap reflects operational experience rather than theoretical preference.

5.3.6 Patterns across Driver Categories

Table 5.4 below presents the frequency with which participants identified interconnections among the five driver categories. Economic incentives and secondary markets exhibited the strongest association (reported by 10 of 13 participants), followed by spatial vulnerability and social fragmentation (9 of 13), and social fragmentation and non-reporting (11 of 13). Participants least frequently connected insider threats with spatial factors (3 of 13).

Table 5.2: Driver Interconnection Matrix (Frequency of participants identifying connections between driver categories (n=13))

	Economic Incentives	Spatial Vulnerability	Social Fragmentation	Insider Threats	Secondary Markets
Economic Incentives	—	7	6	5	10
Spatial Vulnerability	7	—	9	3	6
Social Fragmentation	6	9	—	7	8
Insider Threats	5	3	7	—	6
Secondary Markets	10	6	8	6	—

Note: Values indicate the number of participants (out of 13) who described relationships between driver pairs. Bold values (≥ 9 participants) represent the strongest interconnections: Economic incentives ↔ Secondary markets (10); Spatial vulnerability ↔ Social fragmentation (9). Matrix demonstrates a pattern of multiple reinforcing relationships rather than linear causality. Frequencies are used for transparency about the prevalence of observed connections.

Figure 5.1 below visualises these interconnections as identified by participants. Solid arrows indicate direct causal relationships; dashed arrows represent enabling conditions. The diagram illustrates multiple reinforcing feedback loops: economic incentives create demand in secondary markets (P5, P6, P7, P11, P13); spatial vulnerabilities produce isolation effects that reduce social oversight (P1, P8, P9); insider threats exploit information asymmetries to enable organised rather than opportunistic theft (P2, P6, P9). These patterns accord with the INPUT component of the SETS framework (Chapter 1, Figure 1.2), populating the drivers that create infrastructure vulnerability.

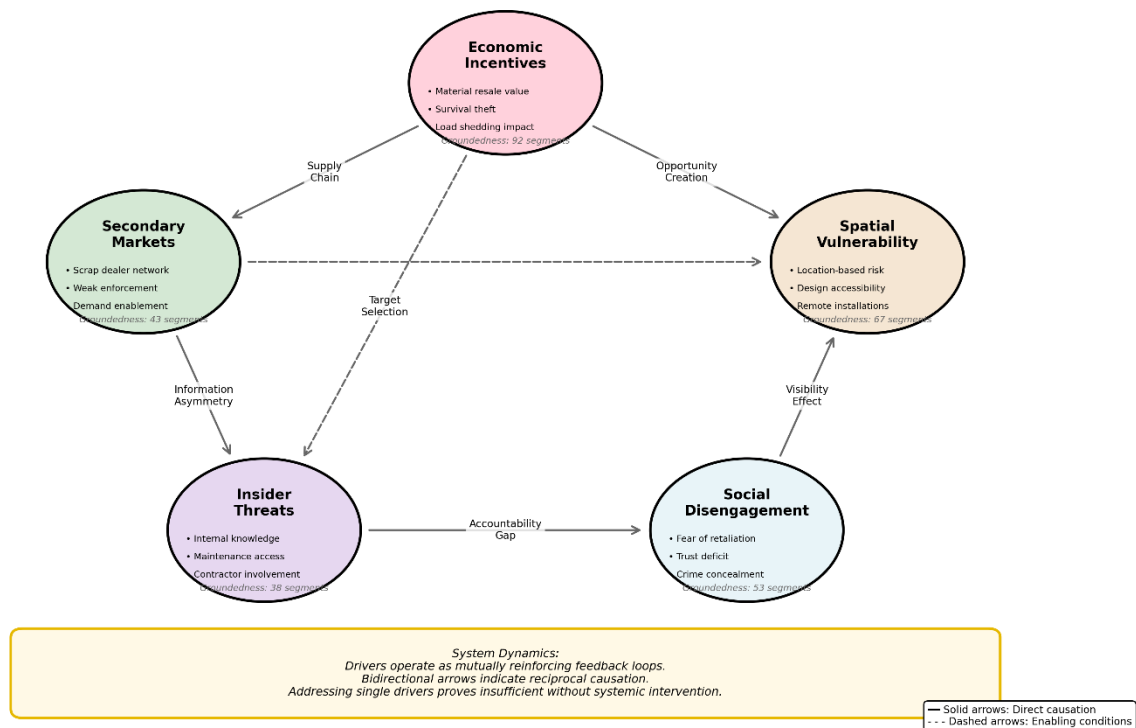


Figure 5.1 Interconnected Drivers of Solar Street Lighting

Note: *values* indicate *the* number of participants (out of 13) who described relationships between driver pairs. Bold values (≥ 9 participants) represent *the* strongest interconnections: *economic* incentives ↔ *secondary* markets (10); *spatial* vulnerability ↔ *social* fragmentation (9). Matrix demonstrates a pattern of multiple reinforcing relationships rather than linear causality. Frequencies *are* used for transparency about *the* prevalence of observed connections.

5.4 Institutional and Technical Responses: Implementation Gaps and Co-ordination Challenges

Research Question 2: How effective are current institutional and technical strategies in preventing solar infrastructure vandalism?

Participant assessments reveal gaps between technical sophistication and institutional effectiveness. While municipalities deploy advanced deterrent technologies like tamper-proof hardware, IoT monitoring, and concrete mounting of luminaires, these interventions operate within fragmented governance structures. Four patterns emerged: technical solutions providing partial protection at prohibitive costs; institutional co-ordination failures fragmenting response capacity; cost-effectiveness tensions where security investments approach replacement costs; and monitoring systems lacking response mechanisms.

5.4.1 Technical Deterrents: Effectiveness and Limitations

Municipalities have invested in anti-vandalism design: tamper-proof fasteners requiring specialised tools; reinforced mounting using concrete poles; elevated component placement; physical barriers such as spikes and fencing; and real-time IoT monitoring. These provide some deterrence against opportunistic theft. P2 explained: “Tamper-proof and reinforced mountings for panels, luminaires and batteries help by requiring specialised tools. More effective still are physical barriers, spikes, barbed wire, and fencing that restrict access. Offenders typically seek the weakest link where the effort required exceeds the expected gain.”

Technical hardening proves effective against opportunistic theft, requiring accessible tools and short working periods. However, multiple participants reported that organised groups overcome hardened systems through specialised equipment and extended working time in surveillance-gap locations. P4 noted: “For solar high-masts, we have not yet experienced theft of structure. Locking mechanisms and specialised keys restrict access. For street lights, specifications include anti-climb ring spikes and collars. But in remote locations or during extended periods without patrol, even these measures get breached.”

Across participant accounts, technical deterrence effectiveness exhibits a correlation with criminal organisation level and surveillance presence. Several participants described

incidents where not just components, but entire poles were removed, concrete bases included, indicating escalation beyond component theft to infrastructure dismantling.

Security-maintenance trade-offs emerged as a second limitation. Hardening and protecting against theft complicates legitimate maintenance. P11 explained: “Every security feature adds maintenance complexity. Specialised fasteners require specialised tools that our crews must carry. Elevated placement means aerial equipment for every repair. The harder we make theft, the harder we make our own work. We optimise for security but degrade operational efficiency.”

This trade-off impacts total ownership cost and system reliability. Hardened infrastructure requiring specialised equipment for repairs extends downtime, reducing service delivery effectiveness. P3 noted: “The design differs. With solar, all key connections can be placed high on a pole, reducing risk. But this assumes the problem is access. When you have organised groups with trucks and power tools, design features only slow them down slightly.”

5.4.2 Institutional Co-ordination Challenges

Multiple entities hold partial responsibility: the municipality’s asset management, Metro Police for law enforcement, SAPS for serious crime, and Community Policing Forums for intelligence. Yet no single actor co-ordinates across jurisdictions. Participants described co-ordination failures manifesting as delayed response, jurisdictional disputes, and information silos (11 of 13 participants).

P8 stated: “City Power is trying, but mandates are split. Some actions require SAPS, others Metro Police. Departments often work in silos. JMPD may avoid acting if not formally tasked. We need integrated protocols, so the right unit is alerted immediately, with clear accountability.”

P2 added: “Lighting affects neighbourhood safety and commerce. Multiple stakeholders must be involved: municipalities, SAPS, private security, businesses and communities. An integrated strategy is needed but remains absent.”

P8's account illustrates what participants characterised as a co-ordination paradox: when multiple entities hold partial responsibility, no single actor accepts accountability for rapid response. By the time appropriate responders are identified and mobilised, offenders have fled. Specialisation is intended to create efficiency fragments response capacity.

5.4.3 Cost-Effectiveness Tensions

Several participants noted situations where security investments approach infrastructure replacement costs. P6 stated: "Security is the most effective safeguard, but extremely expensive. One cannot guard an entire city. Stronger bylaws and consistent enforcement against theft and buying stolen goods would help. We are one of the largest municipalities; a few officials cannot monitor everything."

P5 elaborated: "Budgets matter, but adding security features can triple costs. Laws also need attention: our framework often favours perpetrators over victims. We need clearer criminal categories for infrastructure crime and tools like micro-dot identifiers to track components."

These observations reveal how narrowly focused interventions create cost escalation cycles. Municipalities invest in tamper-proofing, which drives organised criminals to bring better tools, which in turn drives municipalities to add monitoring systems that then require response capacity, leading to additional budget demands. When security costs approach infrastructure value, economic logic becomes challenging.

5.4.4 Detection-Response Gaps

Multiple participants described monitoring systems detecting vandalism events without corresponding response capacity (P3, P5, P13). P3 explained: "We are introducing smart controllers within luminaires so we can detect abnormal events and trigger a response. But detection only helps if response capacity exists. If system alerts show tampering but no one can respond for hours, offenders have time to complete theft."

This detection-response gap extends beyond physical intervention to legal response. P5 noted: “Technology helps, but system response matters most. Offenders are sometimes caught, yet post-arrest outcomes are weak. We need offence categories and sentencing reflecting public harm. Technically, micro-dotting and asset marking can link recovered items to theft, but only if buyers face consequences.”

P13 characterised current monitoring implementations as exhibiting “symbolic compliance with limited operational effect” when response protocols remain absent or under-resourced. Six of nine municipal participants reported having monitoring systems; only two (P3, P13) described functioning response protocols linking detection to rapid intervention. Where protocols existed, average response time ranged from 45 minutes to three hours (P3, P13), during which determined offenders could complete theft.

Across participant accounts, monitoring effectiveness correlated more strongly with response protocol clarity and resource commitment rather than with sensor sophistication. P12 described a successful implementation: “We have real-time alerts linked to contracted security response within 15 minutes. The combination works. Detection without response does not.”

5.4.5 Patterns in Response Effectiveness

Participants consistently reported greater confidence in technical solution potential than in institutional co-ordination capacity. Nine participants described technical interventions (hardening, monitoring) as “partially effective” or “helpful against opportunistic theft,” while 11 characterised institutional co-ordination as “absent,” “fragmented,” or “insufficient.” However, all 13 acknowledged that technical effectiveness depends on institutional support: monitoring requires response protocols, hardening requires maintenance capacity, and deterrents require enforcement backing. Table 5.6 summarises participant assessments of current response strategy effectiveness across different vandalism types and contexts.

Table 5.3: Response Strategy Effectiveness by Context

Response Strategy	Opportunistic Theft	Organised Crime	Remote Location	High Surveillance
Technical Hardening	Effective (9/9 discussed)	Limited (4/9)	Limited (3/9)	Effective (8/9)
IoT Monitoring	Effective (6/6)	Moderate (3/6)	Limited (2/6)	Effective (5/6)
Community Participation	Effective (9/13)	Moderate (5/13)	Limited (2/13)	Effective (11/13)
Enforcement Action	Limited (3/13)	Limited (2/13)	Very Limited (1/13)	Moderate (6/13)
Integrated Response	Effective (4/4)	Effective (3/4)	Moderate (2/4)	Effective (4/4)
PATTERN	Best results	Major challenge	Major challenge	Best results

Note: Parenthetical values show (participants describing this strategy in this context/total discussing context). Qualitative assessments: “Effective” = sustained reduction in vandalism reported; “Moderate” = temporary improvement; “Limited” = minimal impact. Frequencies indicate the prevalence of participant observations; they do not represent quantitative effectiveness measures. Integrated approaches combining multiple strategies showed the highest effectiveness across all contexts.

These findings correspond to the Institutional and Technical Response mechanisms in the SETS framework (Chapter 1, Figure 1.2), revealing how sophisticated capabilities operate within fragmented governance structures. Participants characterised current approaches as addressing symptoms (replacing stolen components) rather than enabling conditions (unco-ordinated response, absent enforcement, resource constraints).

5.5 Community Participation: Between Asset and Absence

Research Question 3: How does community participation impact the resilience of solar street lighting?

Community participation emerged as a simultaneously promising protective mechanism and difficult to sustain. Four themes characterise community dynamics: protective mechanisms when present; structural barriers preventing effective participation; trust deficits rooted in governance failures; and the awareness-action gap, where knowledge exists without corresponding protective behaviour.

5.5.1 Protective Mechanisms and Success Conditions

Where community participation functions effectively, it provides surveillance, early warning, and deterrent effects that technical systems cannot replicate. Participants described successful examples involving formal structures like Community Policing Forums and informal networks like neighbourhood communication groups.

P12 explained: “Maintenance teams run interventions with councillors to co-ordinate replacements and encourage CPF night checks. Private security patrols, but cannot be everywhere. Community eyes provide coverage security companies cannot afford.” This reveals community participation’s value proposition: distributed, continuous presence across the infrastructure footprint. Unlike patrol vehicles passing periodically or cameras monitoring fixed locations, engaged communities provide comprehensive, real-time awareness. When functioning, this creates deterrent effects where potential offenders recognise surveillance risk.

Four participants (P1, P9, P12, P13) described contexts where participation materialised into sustained protective behaviour. Success conditions emerged clearly: trusted leadership, transparent communication, visible municipal responsiveness, and safety assurances, making reporting viable.

5.5.2 Structural Barriers to Effective Participation

Multiple barriers prevent effective community involvement. Meeting timing conflicts with work schedules, excluding employed residents. P1 noted: “Organisation and timing. Meetings are often scheduled when people are resting or preparing for the week, which reduces attendance. Still, residents should make time to protect their community. Where we do engage, people also support one another.”

This logistical issue has implications for participation representativeness. Community structures designed for engagement systematically exclude the employed, skewing participation toward unemployed residents who may lack political capital or institutional access to escalate concerns effectively.

A second barrier involves unclear roles and authority. Community members willing to act lack clarity on appropriate or effective actions. P6 stated: “Policies can be drafted, but action, awareness and knowledge are decisive. We tell communities these are their assets, and they are custodians. Policy should be coupled with participation and education.”

This framing reflects a responsibility-authority gap: communities are designated as custodians but lack a corresponding mandate or resources for asset protection. Seven participants described community members expressing confusion about their role boundaries and escalation pathways when threats emerge.

5.5.3 Trust Deficits and Governance Failures

Fear of retaliation combines with scepticism that reporting yields results. P7 stated: “I have seen little interest. Previously, neighbourhood watches patrolled and questioned suspicious activity. Today, many mind their own business. People fear retaliation. Some groups, such as CPFs, are infiltrated by rogue elements who use participation for criminal intelligence.”

P7’s account describes social capital erosion where collective action mechanisms have withered. The infiltration concern proves particularly damaging: when participation structures intended to protect communities become compromised by criminal elements, trust collapses

entirely. Good-faith participants withdraw, leaving structures nominally intact but functionally captured.

P2 observed: “I have not personally observed strong community engagement in my residential areas. It may exist, but it has not been visible to me. Local WhatsApp groups tend to focus on household security rather than public infrastructure.” This observation reveals how communities prioritise private protection over public infrastructure when governments fail to secure either. This represents individually rational behaviour under conditions of governance failure, which at the aggregate level undermines collective infrastructure protection.

5.5.4 The Awareness-Action Gap

Multiple participants expressed frustration regarding an awareness-action gap: communities understand infrastructure importance and often know perpetrators, yet protective action does not follow. P13 explained: “The City undertakes communication and awareness activities about theft and vandalism of infrastructure. In addition, operations and maintenance keep most street lights on continuously. I was told this is done to make theft more difficult, though it is costly.”

P13’s observation reveals municipalities’ recognition that awareness alone proves insufficient, driving operational responses like leaving lights on continuously. This addresses symptoms (deterring theft through illumination) rather than the underlying reasons pertaining to why communities with awareness do not protect infrastructure.

The gap persists because awareness campaigns assume an information deficit, where the actual problem involves a capacity and safety deficit. Communities know vandalism damages service delivery, but knowledge cannot overcome fear of retaliation, lack of confidence in enforcement response, or absence of clear action pathways.

5.5.5 Participation Patterns and Enabling Conditions

Table 5.7 summarises participant-identified conditions associated with effective versus ineffective community participation across the 13 interviews.

Table 5.4: Community Participation Enabling Conditions

Enabling Condition	Effective Cases	Ineffective Cases	Key Participants
Trusted Leadership	7 of 9 contexts	1 of 9 contexts	P1, P9, P12, P13
Transparent Communication	8 of 9	2 of 9	P3, P9, P12
Visible Response to Reports	9 of 9	0 of 9	P3, P7, P12, P13
Protection for Informants	6 of 9	0 of 9	P3, P7, P9, P12
CPF Without Infiltration	5 of 9	8 of 9	P1, P7, P9
Timing Accommodates Employed	3 of 9	0 of 9	P1, P5, P12
Clear Role Definition	6 of 9	3 of 9	P2, P6, P9

Note: Nine participants described specific community participation contexts in detail. “Effective cases” (n=4 contexts) = sustained protective behaviour observed; “Ineffective cases” (n=9 contexts) = nominal structures without substantive engagement. Values show the prevalence of conditions in each case type. Most notable finding: Visible municipal response present in all effective cases, absent in all ineffective cases, suggesting a necessary (though perhaps not sufficient) condition for sustained engagement.

All 13 participants acknowledged community participation potential for distributed surveillance and early warning. However, only four (P1, P9, P12, P13) described contexts where this potential materialised into sustained protective behaviour. Nine participants described participation structures existing nominally but lacking substantive engagement due to fear (P3, P7, P9), timing barriers (P1, P5), role ambiguity (P2, P6), or structural capture (P7).

P12 articulated the protective mechanism where functioning: “When residents know us, trust us, and see us respond to their reports, they become our early warning system.” Conversely, P7 characterised contexts lacking these conditions: “People fear retaliation. Some groups, such as CPFs, are infiltrated by rogue elements who use participation for criminal intelligence.”

These findings populate the MEDIATING component of the SETS framework (Chapter 1, Figure 1.2), revealing community participation as an amplifier of institutional responses when enabling conditions exist, or an accelerator of degradation when absent.

5.6 Governance Requirements for Systemic Resilience

Research Question 4: What governance changes can promote sustainable solar infrastructure management in vandalism-prone areas?

Participants identified comprehensive governance reforms spanning policy frameworks, enforcement mechanisms, community stewardship formalisation, resource allocation, and monitoring protocols. These proposals emerged consistently across both municipal and OEM participant categories.

5.6.1 Policy Frameworks and Institutional Co-ordination

Participants emphasised a need for integrated policy frameworks linking infrastructure protection, economic development, and social inclusion. P3 stated: “We lack incentives for green energy adoption. We also need policies for lifecycle management of equipment, recycling and disposal. There are green papers, but tangible implementation is limited. Policies should create synergy across stakeholders, including international and local partnerships”. P3’s call for policy integration reflects recognition that infrastructure protection cannot succeed as a standalone objective divorced from broader urban development. Participants advocated for policies simultaneously advancing renewable energy adoption, creating economic opportunity, and establishing clear institutional mandates.

Co-ordination mechanisms emerged as a critical gap. P12 explained: “Maintenance teams also run interventions with councillors to co-ordinate replacements and encourage CPF night checks. Private security does patrols but cannot be everywhere. We need integrated protocols defining when each actor responds.”

5.6.2 Enforcement Mechanisms and Legal Framework Reform

Participants identified enforcement gaps as a critical governance failure. Current legal frameworks treat infrastructure vandalism as petty property crime rather than economic sabotage. P10 proposed: “Harsh punishment could be a cheaper solution. Policies could be changed so that if you are found destroying municipal infrastructure, you face a mandatory minimum sentence, like 10 years in jail, similar to laws for illegal gun possession. I think that could be the cheapest way of discouraging vandalism.”

While P10’s proposal emphasises penalty severity, other participants focused on conviction capacity. P3 stated: “Improve SAPS performance and conviction rates. If theft of infrastructure brings serious sentences, deterrence improves. Conviction rates are low at present. If the offence is widely understood not to be petty, and sentences reflect sabotage where appropriate, offenders will think twice.”

P3’s emphasis on conviction over sentencing as a primary gap reflects participant assessment that harsh penalties prove meaningless if arrest and prosecution rates remain negligible. Seven participants advocated for both classification changes (recognising infrastructure crime as a serious offence) and investigative capacity building.

5.6.3 Formalising Community Stewardship Roles

Participants advocated formalising community roles with clear mandates and support. P9 stated: “Civic education and collaboration: Intensify public education, make communities partners in safeguarding infrastructure. Give them clear roles and escalation paths when threats emerge.”

The language shift from awareness to partnership signals recognition that current approaches treat communities as passive recipients of services rather than active co-producers of infrastructure resilience. Six participants explicitly used “partnership” terminology, emphasising the need for clear roles, training, communication channels, and assurance that participation will not expose members to retaliation.

5.6.4 Strategic Resource Allocation

Budget constraints emerged as a persistent theme, yet participants emphasised allocation strategy over absolute amounts. P3 and P4 stated: “Put money behind clear, enabling policies that drive adoption and protect assets. Budget: Solar units cost more than conventional; adequate funding is needed for city-wide rollout. Capacity and maintenance knowledge: train City personnel on technology and maintenance to reduce reliance on external providers and lower lifecycle costs.”

This reveals participant preference for capability building over perpetual contracting. Current models create dependency on external providers for routine maintenance, driving long-term costs. Five participants advocated for strategic allocation toward internal capacity development to reduce vulnerability while improving response times.

5.6.5 Systematic Monitoring and Evaluation

Participants noted the absence of systematic monitoring protocols linking detection, response, and learning. P13 explained: “Regarding crime prevention, collaboration between City, Metro Police or SAPS, and communities is needed, supported by cameras and telemetry so the Control Centre can monitor assets. Alerts should distinguish accidental damage from vandalism, enabling appropriate response.”

P13’s description emphasises integrated monitoring systems combining technical sensors, institutional response protocols, and community intelligence. The distinction between accident and vandalism reflects the need for a nuanced response, avoiding overreaction to non-criminal damage while ensuring rapid response to theft.

5.6.6 Governance Reform Themes

Participants' governance proposals span multiple institutional levels and domains. Table 5.8 summarises the frequency with which different governance reforms were mentioned across participant categories.

Table 5.5: Governance Reform Proposals by Participant Category

Governance Reform Type	Municipal Engineers (n=9)	OEM Professionals (n=4)	Total (n=13)	Prevalence
Cross-Institutional Co-ordination	8	3	11	Near universal
Integrated Policy Frameworks	7	3	10	Majority
Secondary Market Regulation	8	2	10	Majority
Enforcement Reform	6	3	9	Majority
Formalised Community Partnership	6	2	8	Substantial
Resource Allocation (capacity)	6	2	8	Substantial
Systematic Monitoring Protocols	3	2	5	Some

Note: Values show the number of participants who proposed each reform type. Qualitative prevalence descriptors: Near universal (11+ participants); Majority (eight to ten); Substantial

(six to seven); Some (four to five); Few (two to three). Cross-institutional co-ordination and secondary market regulation emerged as the most consistently prioritised reforms across both participant categories, demonstrating strong convergence despite different organisational perspectives.

Eight or more participants advocated for: integrated policy frameworks (ten participants), enforcement reform treating vandalism as a serious crime (nine participants), formalised community partnership structures (eight participants), and strategic resource allocation prioritising capacity building (eight participants). Fewer participants specified monitoring protocol needs (5 participants), though all acknowledged current systems' limitations.

These proposals correspond to the governance arrangements component in the SETS framework (Chapter 1, Figure 1.2), representing institutional architecture participants characterised as necessary for sustained infrastructure resilience. Current fragmented approaches — separate policies for renewable energy, crime prevention, and community development — create implementation gaps where no actor co-ordinates across domains.

5.7 Conclusion

Analysis of 13 semi-structured interviews revealed solar street light vandalism in Johannesburg and Tshwane as a systemic vulnerability emerging from interaction among input drivers (economic incentives, spatial factors, social fragmentation, insider threats, secondary markets), fragmented institutional and technical response mechanisms, compromised community participation, and unintegrated governance structures. Findings organised around four research questions systematically populated the SETS framework components introduced in Chapter 1.

Three cross-cutting patterns characterise infrastructure vulnerability across participant accounts. Firstly, single-domain interventions demonstrate limited sustained effectiveness: technical hardening without secondary market regulation (addressed by P2, P5, P7, P11); monitoring without response protocols (P3, P5, P13); community awareness without protection mechanisms (P3, P7, P9, P12). Secondly, multiple reinforcing feedback loops

amplify vulnerability: load shedding increases component demand while degrading municipal capacity (P3, P7, P11); insider knowledge converts opportunistic to organised theft (P2, P5, P9); social fragmentation prevents intelligence-sharing despite community knowledge of perpetrators (all 13 participants). Thirdly, current responses address symptoms rather than structural conditions: component replacement without theft incentive elimination; community education without fear mitigation; technology deployment without institutional co-ordination.

Chapter 6 situates these findings within infrastructure resilience and socio-technical systems literature, examining theoretical implications and developing an integrated resilience framework addressing identified vulnerabilities. The discussion analyses mechanisms underlying observed patterns, explores conditions enabling protective rather than exposing community participation, and articulates governance transformations required for sustained infrastructure resilience in vandalism-prone contexts. The chapter also develops theoretical propositions emerging from findings and examines practical implications for municipalities, OEMs, and policymakers seeking to enhance solar street light resilience in similar urban environments.

Chapter 6: Discussion of Results

6.1 Introduction

This chapter interprets the findings from Chapter 5 through the socio-ecological-technical systems (SETS) framework, positioning solar street lighting as an empirical window into broader infrastructure vulnerability mechanisms rather than a technology-specific anomaly. The analysis moves beyond treating vandalism as isolated criminal behaviour to reveal how technical, social, and institutional dimensions interact to generate systemic fragility. Where existing literature compartmentalises these dimensions, treating infrastructure protection as primarily an engineering problem amenable to technical hardening (Belloni et al., 2024; Vidaković & Vinko, 2023), the findings demonstrate that vulnerability emerges from reinforcing feedback loops across domains that technical interventions alone cannot disrupt.

The discussion engages critically with literature predominantly derived from Western contexts, interrogating assumptions that community participation functions uniformly across different governance landscapes (Sahle, 2019; Stott, 2018) or that resource constraints represent implementation barriers rather than fundamental design parameters (Mutumbi et al., 2024). Chapter 5 revealed that vandalism operates as systemic dysfunction rather than deviance, that institutional responses remain fragmented despite technical sophistication, that community participation faces structural barriers transcending awareness campaigns, and that governance reforms require reconfiguration rather than incremental adjustment. These patterns compel theoretical extension beyond technology-specific explanations toward understanding infrastructure resilience as an emergent property of socio-technical-institutional coupling.

The empirical contribution extends beyond documenting solar infrastructure challenges. The findings reveal what this research terms the “systemic adaptation” dynamic: where technical solutions in one infrastructure domain merely displace rather than resolve underlying risks, perpetuating vulnerability through criminal adaptation to new opportunity structures. Participants described how municipalities deploy solar systems partly to reduce copper cable

theft from conventional grid-connected street lights, yet solar components (batteries, panels, charge controllers) rapidly become theft targets through the same mechanisms driving conventional infrastructure vandalism. This technology-switching paradox demonstrates that vandalism does not stem from infrastructure type but from socio-institutional conditions that technical substitution leaves unaddressed. The pattern suggests that findings from solar street lighting inform conventional infrastructure protection more broadly, not because technologies share components but because they exist within identical socio-institutional contexts generating vulnerability.

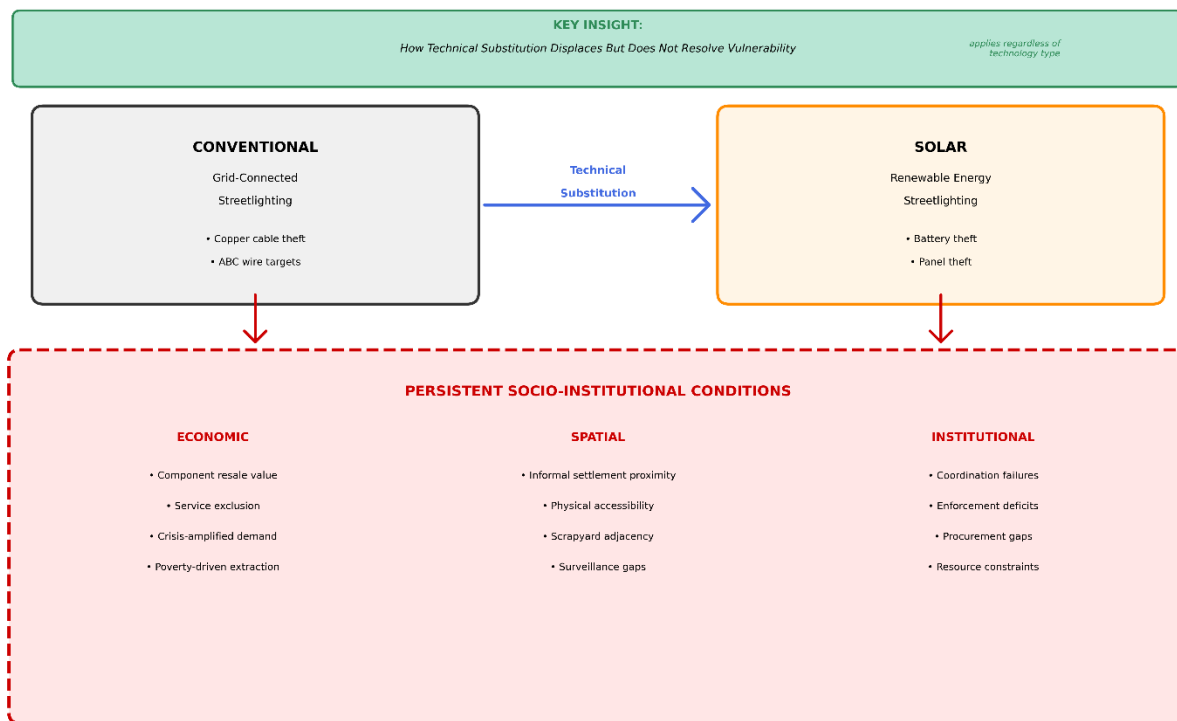


Figure 6.1: The Technology-Switching Paradox - How Technical Substitution Displaces but Does Not Resolve Vulnerability

Figure 6.1 illustrates the technology-switching dynamic observed in the study, where offender adaptation tracks the most marketable and accessible Solar street lighting components unless guardianship and response are strengthened.

This pattern explains the mixed outcomes of technical hardening reported in Chapter 5 and motivates Proposition P2 (governance–technology coupling).

Scope and Context: These findings emerge specifically from solar street lighting infrastructure in Johannesburg and Tshwane metropolitan areas, characterised by high vandalism rates, chronic municipal resource constraints, load shedding contexts amplifying component demand, and populations largely excluded from formal economic participation. The SETS framework and theoretical propositions developed here apply most directly to similar resource-constrained urban contexts where spatial inequality, weak institutional co-ordination, and service exclusion interact to generate infrastructure vulnerability. Transferability to other contexts requires attending to these boundary conditions rather than assuming universal applicability.

The SETS framework proves essential because solar infrastructure resilience cannot emerge from technical hardening alone, community mobilisation without institutional support, or policy reform disconnected from implementation constraints. Each research question receives treatment through this integrative lens, examining how socio-technical-institutional interactions generate vulnerability patterns and identifying co-ordination requirements for effective intervention. The structure addresses each research question while building toward four propositions that extend resilience theory beyond technology-specific explanations to accommodate infrastructure governance realities in resource-constrained contexts.

Section 6.2 interrogates vandalism drivers as system-generated vulnerability emerging from reinforcing feedback loops. Section 6.3 examines why technical and institutional strategies demonstrate limited effectiveness within fragmented governance architectures. Section 6.4 explores how community participation requires safety architectures addressing retaliation risks before expecting protective engagement. Section 6.5 considers governance reforms enabling co-ordination across policy domains and institutional boundaries. The synthesis advances theoretical propositions grounded in solar street lighting evidence while maintaining attention to systemic adaptation dynamics that transcend technology choice, positioning findings as informing infrastructure resilience more broadly rather than applying only to solar systems.

6.2 System-Generated Vulnerability: Reinforcing Feedback Across Domains

Research Question 1: What are the key drivers of vandalism affecting solar street lighting in Johannesburg and Tshwane?

Existing literature treats infrastructure vandalism through binary lenses of economic rationality (Umoh, 2025) or social disorganisation (Lunga et al., 2025), positioning theft as either calculated profit-seeking or a manifestation of community breakdown. This framing obscures the mechanism through which solar infrastructure vulnerability actually operates. The findings demonstrate that vandalism emerges not from single causes but from reinforcing feedback loops connecting economic incentives, spatial opportunities, and institutional gaps. More critically, these feedback mechanisms operate identically whether infrastructure deploys solar or conventional technology, revealing vulnerability as a governance outcome rather than an engineering challenge.

The SETS framework illuminates how these domains interact multiplicatively rather than additively. Economic incentives alone do not determine theft patterns; they are activated through spatial opportunity structures that institutional gaps fail to constrain. This interaction produces the systemic adaptation dynamic where technical substitution (conventional to solar) reproduces rather than resolves vulnerability because underlying socio-institutional conditions remain unchanged. Understanding this mechanism requires examining how each domain reinforces others to generate persistent infrastructure fragility.

Economic Incentives and Crisis Amplification

Chapter 5 documented three distinct economic motivations: survival theft, where infrastructure provides resource access for populations excluded from formal services; opportunistic criminality targeting components with established monetisation pathways; and crisis-amplified demand during load shedding when solar components commanded premium prices. These patterns transcend technology type. When participants described residents near informal settlements extracting ABC cable from conventional grid-connected street lights for illegal electricity connections, while solar systems faced battery and panel theft driven by

household backup power needs, they revealed how the same service exclusion manifests through different technical configurations. Both reflect populations accessing essential services through informal means because formal provision remains inaccessible.

The load shedding dynamic proves particularly instructive for understanding systemic adaptation. Literature treats backup power adoption as a rational response to grid unreliability (Todd & McCauley, 2021; Tshabalala et al., 2025). Yet the same crisis justifying solar street light deployment simultaneously elevates component market value, intensifying theft. Participants estimated theft incidents occurring two to three times more frequently during intensive load shedding periods compared to normal conditions. This creates a perverse feedback loop where infrastructure deployed to address energy insecurity becomes less viable because that same insecurity drives theft. Technical substitution (solar for conventional) cannot disrupt this cycle because it emerges from broader energy access failures that technology choice leaves unaddressed.

This pattern extends beyond solar systems. Copper cable theft from conventional street lights responds to identical economic incentives: component resale value, poverty-driven resource extraction, and crisis-amplified demand during periods of electricity scarcity. The technology-switching paradox demonstrates that moving between infrastructure types displaces theft patterns without resolving underlying drivers. Municipalities face impossible choices: deploy solar to reduce copper cable theft, yet watch batteries and panels become new targets; harden solar components yet see theft shift to more accessible units or different infrastructure types. Technical solutions operating within unchanged socio-institutional conditions merely redistribute rather than reduce vulnerability.

Spatial Opportunity Structures

Economic incentives are activated through spatial configurations that create differential vulnerability. Chapter 5 revealed three spatial risk factors: proximity to informal settlements and scrapyards where component resale networks concentrate, physical accessibility of valuable components in publicly exposed locations, and remoteness from surveillance or community oversight enabling unwitnessed theft. These spatial patterns operate identically

for solar and conventional infrastructure, demonstrating that opportunity structures reflect socio-spatial configurations rather than technology characteristics.

Infrastructure near informal settlements faces dual pressures, enabling illegal connections and facilitating component resale through local informal economies. Participants universally identified this proximity as a primary spatial risk factor, describing persistently higher vandalism rates despite technical hardening measures. This spatial pattern complicates technical responses: hardening components may deter opportunistic theft, but address neither underlying access deprivation driving illegal connections nor socioeconomic conditions enabling component markets. Solar panels mounted on poles prove no more or less vulnerable than copper cable running underground when located near populations excluded from formal services and adjacent to informal resale markets.

The accessibility dynamic reveals how design decisions distribute vulnerability without eliminating it. Solar systems concentrate valuable components in publicly accessible locations; conventional grid-connected systems hide infrastructure underground but expose cables through connection points. Both face accessibility trade-offs between maintenance requirements and theft exposure. Participants described how every design choice involves trade-offs rather than solutions: all-in-one sealed luminaires reduce field cabling theft risk but concentrate component value in single accessible units; distributed component systems reduce single-point theft value but multiply access opportunities. Technical configuration shifts but does not eliminate the accessibility-vulnerability tension when spatial opportunity structures remain constant.

Remoteness amplifies vulnerability through the absence of natural surveillance regardless of technology type. Arterial roads and highways lack the passive community oversight that characterises residential areas. Whether infrastructure deploys solar panels or conventional cable, theft in these locations often progresses to complete system dismantling because offenders face minimal interruption risk. Across participant accounts, installations in three contexts exhibited the highest vulnerability regardless of technical specification: proximity to informal settlements where service exclusion concentrates, adjacency to scrapyards enabling component monetisation, and remoteness from natural surveillance. These spatial patterns

persist across technology choices because they reflect socioeconomic geography rather than engineering decisions.

Institutional Gaps Enabling Persistent Vulnerability

Economic incentives and spatial opportunities convert into actual theft when institutional mechanisms fail to constrain exploitation. Chapter 5 documented co-ordination failures across departments responsible for street lighting (energy, roads, safety, and finance) operating in isolated silos, enforcement gaps where police lack the capacity to investigate infrastructure theft systematically, and procurement weaknesses enabling component substitution and quality compromises. These institutional deficiencies affect solar and conventional infrastructure identically, revealing governance capacity as a determinant of vulnerability independent of technology choice.

Co-ordination failures manifest in fragmented responses where no single entity owns comprehensive infrastructure protection. Energy departments specify technical requirements without consulting safety officials who understand crime patterns; procurement specialists evaluate bids without maintenance team input on component accessibility and repairability; finance departments allocate capital expenditure for installation, but insufficient operational budgets for monitoring and rapid response. This fragmentation creates implementation gaps where sophisticated technical specifications meet inadequate surveillance, enforcement, and maintenance capacity. Whether infrastructure deploys solar or conventional technology becomes irrelevant when institutional co-ordination cannot support implementation.

The insider threat reveals how institutional knowledge gaps create systematic vulnerability. Multiple participants described theft perpetrated or facilitated by individuals with technical knowledge of system specifications, maintenance schedules, and monitoring gaps. Former contractors, dismissed employees, and current staff with financial motivations exploit institutional knowledge to circumvent protections. This dynamic transcends technology type. Solar system access codes and conventional grid connection points both require insider knowledge for efficient exploitation. Technical hardening proves ineffective when institutional employment and contracting practices do not screen for integrity or when compensation proves insufficient to deter the monetisation of insider knowledge.

Enforcement gaps compound institutional failures. Participants consistently reported minimal police capacity for infrastructure theft investigation, describing how officers lack technical training to understand solar system components or conventional electrical infrastructure. Even when perpetrators are identified, prosecution proves rare due to resource constraints and competing priorities. This creates impunity feedback loops where successful theft emboldens further attempts. The enforcement gap affects all infrastructure types equally. Solar batteries were stolen and conventional copper cable removed, both enter secondary markets with minimal legal consequence because enforcement capacity cannot expand to match theft volume.

The four propositions that emerge from these findings work as an integrated system, each addressing a distinct dimension of infrastructure resilience while reinforcing others. Figure 6.2 illustrates how these propositions converge around infrastructure resilience as a central outcome operating across spatial, technical and institutional dimensions.

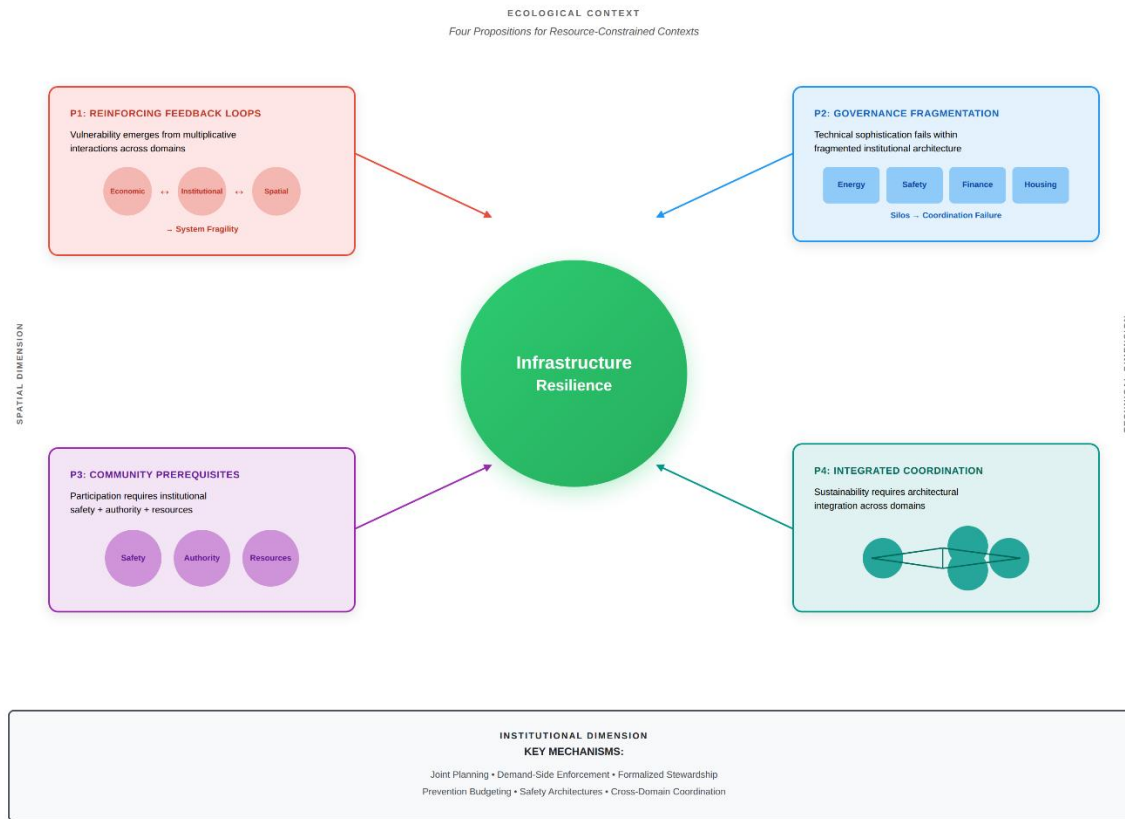


Figure 6.2: Integrated SETS Framework showing how the four theoretical propositions work together as an interdependent system

Proposition 1: Urban infrastructure vulnerability emerges from reinforcing feedback loops between economic incentives, spatial opportunities, and institutional gaps. Technical interventions addressing single domains prove insufficient because vulnerability persists through interactions across socio-technical-institutional dimensions. The systemic adaptation dynamic where technology substitution reproduces rather than resolves theft patterns demonstrates that infrastructure protection requires disrupting feedback loops rather than optimising isolated components. This mechanism extends beyond solar street lighting to inform understanding of infrastructure vulnerability more broadly, as the same reinforcing

interactions generate persistent fragility across technology types when underlying socio-institutional conditions remain unchanged.

6.3 Technical Sophistication within Fragmented Governance: Why Isolated Interventions Fail

Research Question 2: How effective are current institutional and technical strategies in preventing solar infrastructure vandalism?

Literature often positions technical hardening and institutional capacity building as distinct intervention pathways, with sophisticated engineering solutions (tamper-resistant hardware, IoT monitoring, surveillance systems) presented as primary protection mechanisms that institutional arrangements should support (Belloni et al., 2024; Mourtzis et al., 2020). This framing suggests technical excellence can compensate for governance limitations, with sufficiently robust hardware overcoming institutional constraints. The findings challenge this assumption fundamentally. Technical interventions demonstrate limited effectiveness, not because they lack sophistication but because they operate within governance architectures that fragment responsibility, constrain resources, and prevent co-ordination necessary for implementation success.

The SETS framework reveals why technical and institutional domains must function as coupled systems rather than independent intervention tracks. Technical specifications achieve intended outcomes only when institutional arrangements provide monitoring capacity, maintenance resources, enforcement support, and adaptive management enabling continuous improvement. When governance fragmentation isolates these functions across unco-ordinated departments and budget silos, even sophisticated technical solutions fail to translate into operational resilience. The implications extend beyond solar infrastructure: technical interventions in any infrastructure domain prove insufficient when governance architecture cannot support co-ordinated implementation.

Chapter 5 documented extensive technical innovations deployed to reduce vulnerability: tamper-resistant battery enclosures, sealed all-in-one luminaires, hardened pole materials, and reduced copper cabling. Participants described these measures as effective in deterring opportunistic theft where offenders lack tools or time for sophisticated breaching. Yet multiple participants also reported that hardened measures get circumvented systematically in high-risk locations, particularly during extended periods without patrol or rapid response. The technical sophistication proves irrelevant when institutional capacity cannot sustain surveillance, maintain equipment, or respond to breach attempts before completion.

IoT-enabled monitoring and remote diagnostics represent a substantial technical advancement, enabling real-time fault detection, predictive maintenance, and breach alerts. Yet participants consistently described monitoring systems generating data that institutional arrangements cannot utilise effectively. Alerts about battery depletion or panel removal go unaddressed when municipal structures lack designated response teams, maintenance budgets prove insufficient for timely repair, or co-ordination failures mean energy departments' monitoring systems cannot trigger rapid response from safety officials or repair crews.

CCTV integration with street lighting infrastructure presents similar technical-institutional disconnects. Cameras mounted on light poles offer deterrent value and evidence for prosecution, yet their effectiveness depends entirely on institutional capacity for footage monitoring, rapid response to incidents, and successful prosecution. Multiple participants described surveillance systems installed but underutilised because security operations centres lack personnel for real-time monitoring, footage storage exceeds available server capacity, or co-ordination gaps mean video evidence does not reach police investigators effectively.

Technical specifications prove meaningless when procurement processes allow component substitution and quality compromises, while maintenance arrangements lack the capacity for sustained operational integrity. Chapter 5 documented instances where tender specifications mandated tamper-resistant hardware yet contracted suppliers substituted inferior components, leveraging gaps in municipal inspection capacity and enforcement. This procurement weakness undermines technical interventions at source: sophisticated designs

specified on paper never materialise in actual installations because institutional oversight cannot verify compliance.

Proposition 2: Technical interventions fail when operating within fragmented governance systems, regardless of their technological sophistication. Infrastructure protection requires coupling technical capabilities with institutional arrangements enabling co-ordinated monitoring, response, maintenance, and adaptive management. Technical optimisation within governance constraints proves insufficient because implementation depends on socio-institutional co-ordination that fragmented architectures cannot provide. This principle extends beyond solar infrastructure to any domain where technical solutions encounter institutional fragmentation: absent governance integration, even advanced capabilities remain latent.

6.4 Community Participation Confronting Structural Barriers: Beyond Mobilisation Rhetoric

Research Question 3: How does community participation impact the resilience of solar street lighting?

The literature extensively documents community participation benefits for infrastructure sustainability (Sahle, 2019; Stott, 2018), positioning engagement as a remedy for vandalism through generating social capital, collective efficacy, and protective oversight. This framing treats participation as primarily a mobilisation challenge amenable to awareness campaigns and consultation forums. The findings reveal a more complex reality. Community protection of solar infrastructure requires not merely willingness but institutional safety architectures mitigating retaliation risks, authority over meaningful decisions, and resource access enabling protective action. Without addressing structural barriers constraining engagement, participation rhetoric reproduces tokenism that existing literature critiques (Brear & Tsotetsi, 2022; Tyhotyholo & Ncube, 2023) while failing to generate protective capacity.

The SETS framework illuminates why participation functions as contested political terrain requiring structural transformation rather than a mobilisation technique. Social dimensions of

infrastructure protection couple with institutional arrangements providing legitimacy, resources, and safety mechanisms. When governance architecture cannot supply these enabling conditions, even genuine community willingness to participate proves insufficient for generating protective oversight. This dynamic transcends solar infrastructure: any community-based protection initiative confronts similar structural barriers where engagement rhetoric meets inadequate institutional support.

Retaliation Risk and Safety Architecture Gaps

Chapter 5 documented community members' reluctance to report suspicious activity or confront potential thieves due to retaliation fears. Participants consistently described how residents observing theft in progress avoid intervention because personal safety risks exceed civic duty motivations. This safety calculation reflects a rational assessment of institutional failure to protect participants. Residents who report vandalism or attempt prevention face potential violence without assurance that police will respond effectively, prosecutors will pursue charges, or municipal authorities will provide witness protection. The institutional safety architecture necessary for community engagement remains absent.

This dynamic reveals a fundamental sequencing error in participation approaches. Municipalities call for community involvement without first establishing institutional mechanisms to mitigate participation risks. Residents cannot be expected to assume personal danger when governance architecture fails to provide protective safeguards. Awareness campaigns and consultation forums prove insufficient because they do not address the structural barrier preventing engagement: the absence of safety guarantees. Community members possess the willingness to participate but correctly assess that institutional arrangements cannot protect them from consequences.

Tokenism and Authority Gaps

Multiple participants described consultation processes where community input gets solicited but ignored in actual decision-making. Ward committee meetings occur, residents express preferences about installation locations and design features, yet municipal decisions proceed according to technical or political considerations disconnected from community input. This

tokenistic engagement generates cynicism rather than cooperation. Residents recognise that their participation holds no decision-making authority, correctly assessing that engagement involves extracting information and legitimacy rather than sharing power.

Literature distinguishes tokenistic from authentic participation through authority distribution (Brear & Tsotetsi, 2022). Authentic engagement provides communities with genuine influence over resource allocation, design specifications, and implementation priorities. Yet institutional arrangements in resource-constrained contexts resist this power sharing. Municipal officials maintain technical authority, procurement processes constrain design flexibility, and political considerations override community preferences. The institutional architecture lacks mechanisms for translating community input into binding decisions.

Resource and Capacity Constraints

Community monitoring and maintenance initiatives require sustained resourcing that institutional budgets struggle to provide. Chapter 5 documented calls for community security volunteers, neighbourhood watch programmes, and local reporting networks, yet participants consistently noted the absence of financial support for these initiatives. Volunteers cannot sustain unpaid engagement indefinitely, particularly in communities where poverty makes opportunity costs substantial. Expecting sustained community protection without compensating participants or providing necessary resources reflects unrealistic governance assumptions about civic capacity.

The resource constraint extends to technical capacity for community involvement. Effective monitoring requires understanding what constitutes normal system operation versus breach indicators, reporting pathways connecting community observations to rapid response mechanisms, and training enabling basic troubleshooting, distinguishing maintenance needs from vandalism. However, institutional arrangements rarely provide this capacity building. Community members receive participation mandates without technical training, reporting mechanisms, or confidence that their alerts trigger an effective institutional response.

Spatial Inequality and Participation Viability

Community participation faces differential viability across spatial contexts, reflecting underlying inequality patterns. Chapter 5 revealed that the highest-risk locations (proximity to informal settlements, scrapyards, remote stretches) correspond with contexts where community engagement capacity proves weakest. Informal settlement residents facing service exclusion and economic marginalisation have limited capacity for infrastructure protection volunteerism. Their survival strategies sometimes include extracting resources from infrastructure rather than protecting it, reflecting rational responses to formal service deprivation rather than antisocial behaviour.

This spatial pattern compounds participation challenges. Infrastructure deployed in locations most needing community protection corresponds with communities least able to provide it without substantial institutional support. Yet institutional arrangements treat participation as uniformly viable across contexts, applying standardised engagement approaches regardless of local capacity differences. High-income areas with established neighbourhood associations, social capital, and political influence achieve greater participation success not because residents care more but because socioeconomic conditions enable sustained civic engagement.

Proposition 3: Community protection requires institutionalised safety architectures that mitigate retaliation risks before expecting participation. Beyond safety, effective engagement demands decision-making authority, sustained resourcing, technical capacity building, and recognition of spatial inequality affecting participation viability. Mobilisation rhetoric without institutional enabling conditions generates tokenism rather than protective capacity. This principle applies broadly: community-based initiatives fail when governance architecture cannot provide safety guarantees, power-sharing mechanisms, and resources necessary for sustained engagement.

6.5 Governance Architecture for Sustainable Resilience: Co-ordination over Fragmentation

Research Question 4: What governance changes can promote sustainable solar infrastructure management in vandalism-prone areas?

Literature acknowledges governance importance for infrastructure resilience, yet often positions reforms as incremental improvements within existing architectures: better co-ordination protocols, increased budgets, enhanced training (Cirolia & Harber, 2021). This framing treats governance gaps as capacity deficits amenable to technical assistance and resource augmentation. The findings suggest a more fundamental challenge. Sustainable solar infrastructure resilience requires architectural reconfiguration enabling integration across policy domains (energy, safety, planning, finance) and institutional boundaries (municipal departments, law enforcement, community structures). Incremental adjustments within fragmented governance prove insufficient because co-ordination failures emerge from organisational design rather than merely capacity constraints.

The SETS framework reveals why infrastructure protection demands integrated governance rather than improved silos. Technical specifications, community engagement, monitoring systems, and enforcement mechanisms must function as a co-ordinated whole where each element enables others. When governance architecture fragments these functions across disconnected entities, no amount of technical sophistication or community mobilisation generates resilience because implementation depends on co-ordination that organisational structure prevents. This pattern extends beyond solar infrastructure: any complex socio-technical system requiring multi-stakeholder co-ordination confronts similar governance architecture challenges.

Policy Integration across Domains

Chapter 5 documented co-ordination failures where energy departments specify technical requirements without consulting safety officials who understand theft patterns, procurement processes operate independently from maintenance planning, and finance allocates capital for installation but insufficient operational budgets for sustainment. This fragmentation ensures that even well-designed interventions encounter implementation gaps. Policy integration requires organisational mechanisms linking these domains systematically rather than episodically.

Joint planning mandates represent a structural intervention addressing fragmentation at source. Rather than energy departments developing street lighting strategies independently and then seeking input from safety and maintenance functions, integrated planning assigns joint accountability for infrastructure outcomes across departments. This requires organisational redesign, establishing standing committees with cross-departmental membership, budgets controlled collaboratively, and performance metrics evaluating co-ordination rather than only departmental outputs.

Demand-Side Enforcement

Vandalism persists partly because demand for stolen components remains unaddressed. Chapter 5 documented extensive secondary markets enabling component monetisation through scrapyards, informal traders, and online platforms. Supply-side interventions (hardening infrastructure, increasing surveillance) prove insufficient when demand-side pathways remain unconstrained. Sustainable governance requires co-ordination between municipal authorities and law enforcement to disrupt component markets through scrapyard regulation, online platform monitoring, and informal economy engagement.

Scrapyard licensing and inspection represent demand-side intervention requiring inter-institutional co-ordination. Municipal bylaws can mandate component traceability documentation, yet enforcement depends on police capacity for inspection and prosecution. This co-ordination typically remains weak because municipal licensing authorities and police operate independently with separate priorities and limited communication pathways. Establishing systematic co-ordination requires formalised protocols specifying inspection schedules, information sharing mechanisms, and joint enforcement actions.

Formalised Community Stewardship

Community participation remains rhetorical without institutional mechanisms formalising roles, providing resources, and channelling input into decision-making. Chapter 5 documented community willingness to engage, undermined by the absence of legitimate participation pathways. Governance reform requires creating formal structures that embed community actors within infrastructure management rather than treating them as external consultants. Ward committees could assume designated monitoring responsibilities with

accompanying training and modest compensation. Neighbourhood security structures could receive formal integration with rapid response protocols. Community representatives could hold voting positions on infrastructure planning committees.

This formalisation provides institutional legitimacy and accountability absent from ad hoc engagement. Community monitors with formal designation gain authority to request information, report concerns through established pathways and expect an institutional response. Reciprocally, municipalities gain a legitimate expectation that designated community structures fulfil defined responsibilities rather than sporadic participation dependent on individual goodwill.

Prevention-Oriented Budgeting

Municipal budgeting prioritises capital projects (new installations) over operational requirements (monitoring, maintenance, rapid response) because capital expenditure generates visible political outputs while operational spending remains backstage. This bias ensures inadequate resourcing for sustained resilience. Chapter 5 documented sophisticated technical specifications undermined by insufficient maintenance budgets, monitoring systems deployed without operational funding, and community engagement initiatives unfunded beyond initial mobilisation.

Sustainable governance requires budgeting reforms prioritising lifecycle costs over capital visibility. Infrastructure projects should include mandatory operational budget allocations covering projected monitoring, maintenance, and community engagement expenses. Procurement specifications should evaluate lifecycle cost-effectiveness rather than only upfront capital pricing. Performance metrics should assess operational integrity over time rather than merely installation completion.

Proposition 4: Sustainable infrastructure resilience necessitates integrated governance that co-ordinates across policy domains and institutional boundaries. Joint planning mandates, demand-side enforcement, formalised community stewardship, and prevention-oriented budgeting represent architectural mechanisms enabling co-ordination over fragmentation. These reforms apply broadly beyond solar infrastructure: any complex socio-technical system

requires governance architecture supporting systematic co-ordination rather than episodic consultation. Incremental improvements within fragmented structures prove insufficient because co-ordination failures emerge from organisational design rather than merely capacity constraints.

6.6 Synthesis: Systemic Adaptation and the Limits of Technical Substitution

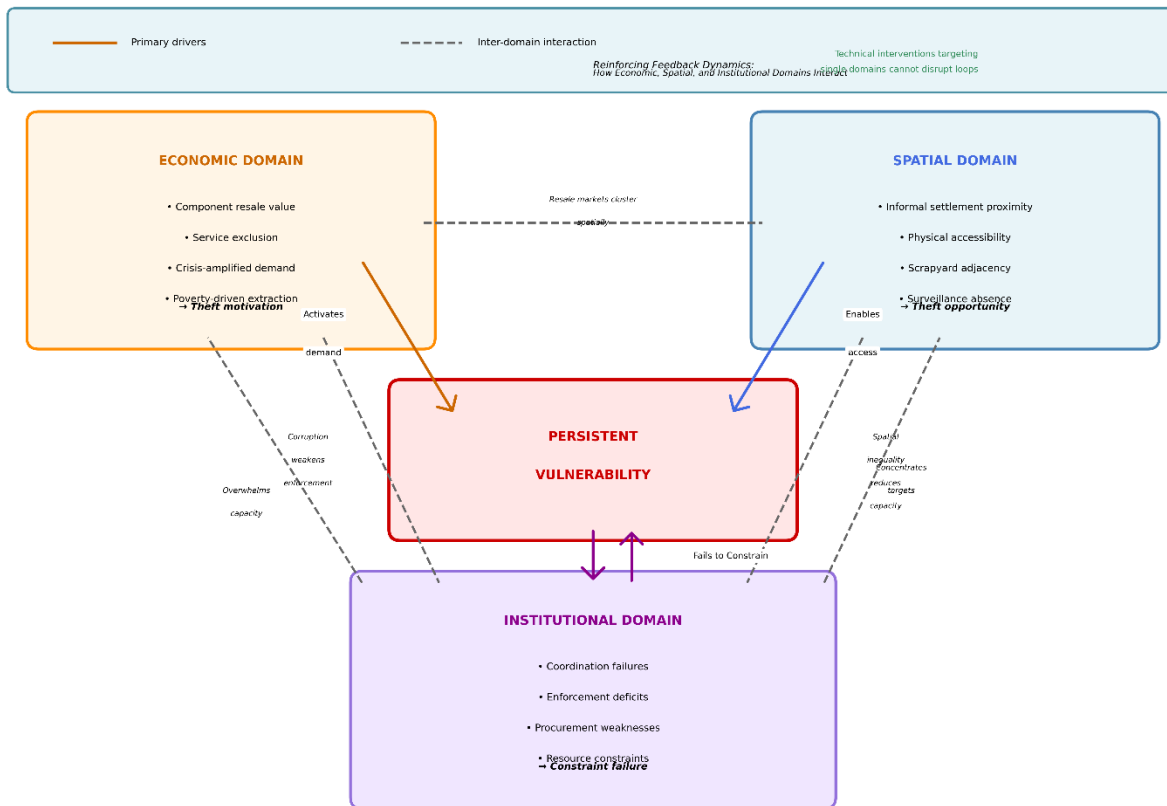


Figure 6.3: Reinforcing Feedback Loops illustrates the multiplicative interactions between economic, spatial, and institutional domains that create persistent vulnerability.

The figure above demonstrates why single-domain interventions fail - the three domains operate as mutually reinforcing feedback loops that sustain persistent vulnerability. Technical interventions targeting any single domain cannot disrupt these interconnected dynamics.

The discussion reveals infrastructure vulnerability as a system-generated property emerging from reinforcing interactions across economic, spatial, social, and institutional dimensions. This conceptualisation extends existing resilience literature focused primarily on external shocks (natural disasters, accidents) to encompass chronic stresses emerging from socio-

institutional conditions (Holling, 1973; Kapucu et al., 2024). The empirical contribution positions solar street lighting not as a technology-specific case but as an empirical window revealing how technical interventions encounter socio-institutional constraints that technology choice cannot circumvent.

The systemic adaptation dynamic observed through this research challenges assumptions underlying technical substitution strategies. Municipalities deploy solar systems partly to reduce copper cable theft affecting conventional grid-connected street lights, yet solar components rapidly become primary theft targets through identical mechanisms driving conventional infrastructure vandalism. This technology-switching paradox demonstrates that vulnerability does not rely on infrastructure type but emerges from socio-institutional conditions that technical substitution leaves unaddressed. Moving from conventional to solar infrastructure displaces theft patterns without resolving underlying drivers: component resale markets, service exclusion generating informal resource access, spatial opportunity structures, and institutional gaps constraining effective protection.

The pattern suggests that findings from solar street lighting inform conventional infrastructure protection more broadly. Not because solar and conventional systems share components or technical characteristics, but because both exist within identical socio-institutional contexts, generating vulnerability. Economic incentives (component value, poverty-driven extraction), spatial opportunities (proximity to informal settlements, physical accessibility), and institutional gaps (co-ordination failures, enforcement deficits) operate equivalently whether infrastructure deploys solar panels or copper cable. Technical differences prove secondary to governance architecture, determining whether institutions can co-ordinate monitoring, community engagement, and enforcement functions necessary for any infrastructure protection.

This positioning constitutes an empirical extension rather than overreach. The SETS framework demonstrates that infrastructure resilience requires a socio-technical-institutional coupling that technology choice cannot escape. Solar systems and conventional infrastructure both depend on institutional capacity for monitoring, community willingness to engage with safety guarantees, and governance co-ordination across fragmented organisational structures. When these socio-institutional conditions remain inadequate,

technical sophistication proves latent. Conversely, when governance architecture enables effective co-ordination, even less advanced technical specifications achieve resilience outcomes. The evidence supports the theoretical proposition that infrastructure vulnerability emerges from socio-institutional coupling quality rather than technical configuration, with solar street lighting providing an empirical demonstration of the broader mechanism.

The four propositions advance resilience theory by specifying mechanisms through which socio-institutional conditions generate infrastructure vulnerability independent of technology choice. These propositions extend the literature treating infrastructure resilience primarily as a technical property (Belloni et al., 2024) or community mobilisation challenge (Sahle, 2019) toward recognising resilience as emergent from socio-technical-institutional coupling. The framework explicitly designs for conditions characterising resource-constrained contexts: service exclusion creating extraction pressure; spatial inequality concentrating vulnerability; weak co-ordination fragmenting responses; and fiscal constraints limiting implementation options. By positioning these conditions as design parameters rather than implementation barriers, the framework enables theoretical development accommodating Global South governance realities rather than treating them as deficient versions of Western models.

Table 6.1: Theoretical Propositions and Mechanisms

Research Question	Proposition	Theoretical Contribution	Key Mechanisms
RQ1: Vandalism Drivers	P1: Reinforcing Feedback Loops - Urban infrastructure vulnerability emerges from reinforcing feedback loops between economic incentives, spatial	Extends resilience literature (Holling, 1973; Kapucu et al., 2024) beyond external shocks to system-generated vulnerability through multiplicative domain interactions	Economic crisis amplification; spatial opportunity clustering; institutional gap exploitation; systemic adaptation across technologies

	opportunities, and institutional gaps		
RQ2: Strategy Effectiveness	P2: Fragmented Governance Constraints - Technical interventions fail when operating within fragmented governance systems, regardless of technological sophistication	Challenges technocentric approaches (Belloni et al., 2024) by demonstrating governance architecture as a precondition for technical effectiveness	Technical-institutional coupling requirements; monitoring-response co-ordination gaps; procurement-maintenance disconnects; CAPEX-OPEX mismatches
RQ3: Community Participation	P3: Safety Architecture Prerequisites - Community protection requires institutionalised safety architectures that mitigate retaliation risks before expecting participation	Extends participation literature (Brear & Tsotetsi, 2022) by specifying structural prerequisites beyond mobilisation	Retaliation risk mitigation; authority distribution; sustained resourcing; spatial inequality recognition; tokenism transcendence
RQ4: Governance Reforms	P4: Integrated Co-ordination Architecture - Sustainable infrastructure resilience	Extends co-ordination literature (Cirolia & Harber, 2021) from capacity building to	Joint planning mandates; demand-side enforcement; formalised stewardship;

	necessitates integrated governance co-ordinating across policy domains and institutional boundaries	architectural specification	prevention- oriented budgeting; cross- boundary mechanisms
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Note: All propositions are grounded in solar street lighting evidence while demonstrating applicability through a systemic adaptation mechanism transcending technology choice. Boundary conditions: resource-constrained contexts with spatial inequality, weak institutional co-ordination, and service exclusion patterns.

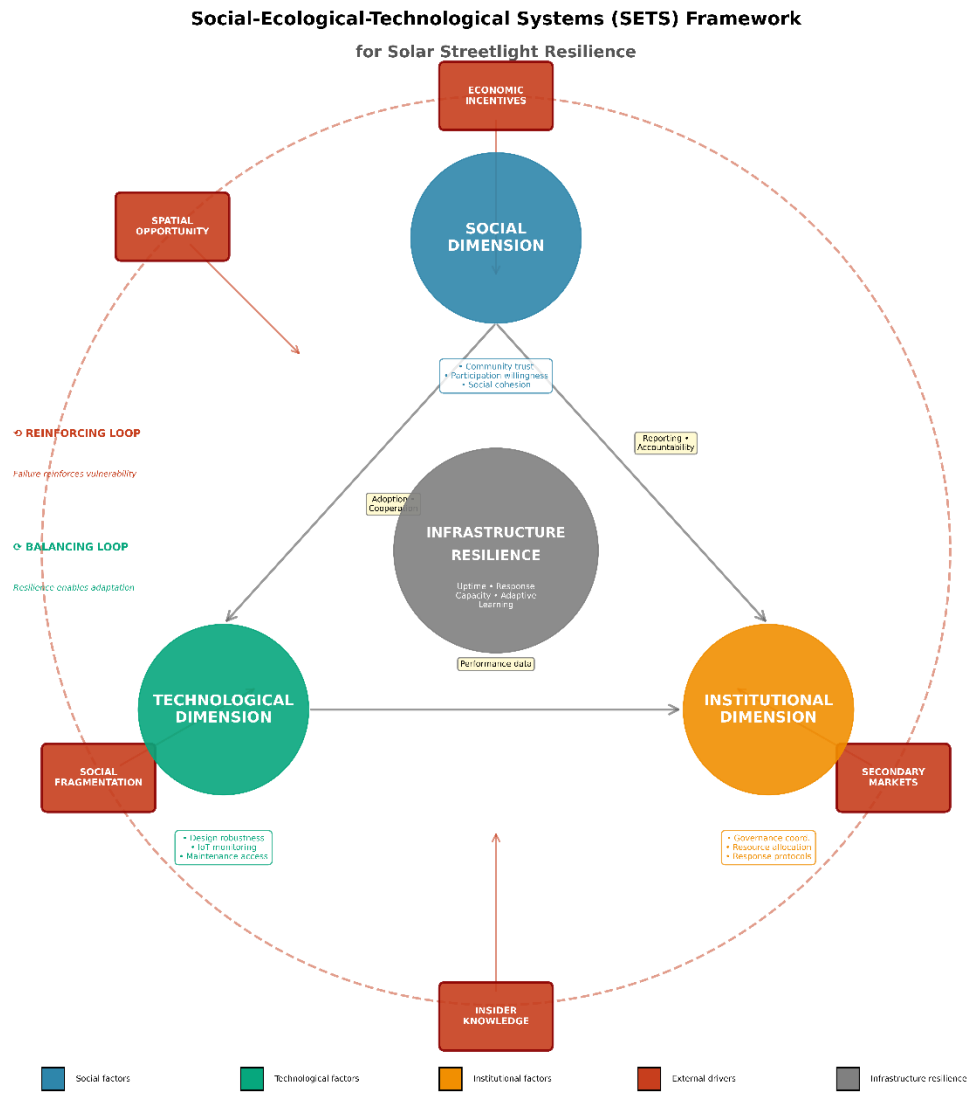


Figure 6.4 Integrated SETS Framework: A Synthesis

Figure 6.4 above presents the SETS (social-ecological-technological systems) framework that emerged from this study's findings. The framework illustrates how any single factor does not determine infrastructure resilience but emerges from the dynamic interaction of three core dimensions: social (community engagement and trust), technological (design and monitoring systems), and institutional (governance and resource allocation). Critically, the framework shows that resilience is undermined by external vandalism drivers that exert pressure on all three dimensions simultaneously, while feedback loops either reinforce vulnerability or strengthen adaptive capacity.

This framework synthesises findings from all four research questions, demonstrating that sustainable infrastructure resilience requires co-ordinated interventions across all social, technical, and institutional domains rather than isolated technical or community-based solutions.

6.7 Limitations of the Study

Sample Composition and Voice Representation

The study captured institutionally mediated community perspectives rather than direct resident voices. Municipal engineers and OEM professionals operate as implementing arms of political mandates that respond to community pressure expressed through ward meetings, service complaints, and electoral accountability. While this approach provided an in-depth understanding of how community concerns shape infrastructure decisions through institutional channels, it represents community needs as interpreted by professional and political intermediaries rather than residents themselves.

This limitation holds particular significance for Research Question 3, which examined community participation mechanisms. Analysis of participation barriers, effectiveness, and enabling conditions draws primarily from professional observations of community engagement rather than residents' own assessments. The study did not include ward committee members, community forum representatives, or residents from informal settlements most affected by vandalism. Consequently, the findings may not fully capture resident agency, informal organising efforts, or community-initiated responses occurring outside formal institutional frameworks.

Future research should complement this institutional perspective with direct community participation, particularly from informal settlements and high-vandalism areas. Participatory research methods, such as community-based participatory research or participatory action research, could enable residents to frame infrastructure challenges in their own terms, identify solutions aligned with local priorities, and articulate how institutional responses align with or diverge from community needs independent of professional or political intermediation.

6.8 Conclusion

This chapter interpreted solar street lighting findings through the SETS framework while positioning solar infrastructure as an empirical case revealing broader vulnerability mechanisms rather than a technology-specific anomaly. The analysis demonstrated that vandalism operates through reinforcing feedback loops across economic, spatial, and institutional domains; that technical sophistication proves insufficient within fragmented governance architectures; that community participation requires institutional safety guarantees, authority distribution, and sustained resourcing; and that sustainable resilience demands governance integration across policy domains and institutional boundaries.

The discussion challenged assumptions embedded in predominantly Western-derived theory: that vulnerability stems primarily from external shocks rather than system-generated exclusions; that technical solutions function independently of governance architecture; that community participation delivers benefits automatically without structural enablement; and that resource constraints represent implementation barriers rather than fundamental design parameters requiring strategies explicitly built for fiscal scarcity. Each assumption fails when confronted with evidence from contexts where large populations lack formal service access, spatial inequality concentrates vulnerability, institutional co-ordination remains chronically weak, and budgets prove persistently inadequate.

Four propositions emerged extending resilience frameworks to accommodate resource-constrained urban contexts. These propositions specify mechanisms (reinforcing feedback loops, governance architecture constraints, safety prerequisites, co-ordination requirements) explaining infrastructure vulnerability as emerging from socio-technical-institutional coupling rather than technical configuration. The empirical contribution positions findings through a systemic adaptation lens: solar street lighting reveals how technical substitution displaces vulnerability patterns without resolving underlying drivers when socio-institutional conditions remain unchanged. This mechanism extends beyond solar systems, informing the understanding of infrastructure protection more broadly while maintaining attention to boundary conditions (resource constraints, spatial inequality, weak co-ordination) characterising contexts where findings apply most directly.

The synthesis advanced a theoretical framework recognising infrastructure resilience in resource-constrained contexts as depending on governance architecture enabling co-ordination across fragmented organisations, institutional safety mechanisms supporting community engagement, and prevention-oriented resource allocation sustaining operational capacity. This framework is explicitly designed for conditions characterising Global South cities rather than treating them as deficient implementations of Western models. It positions infrastructure management as fundamentally political, acknowledging that decisions about deployment, protection, and community participation distribute benefits and burdens, while reproducing or challenging existing inequalities.

Limitations and Transferability: The findings emerge specifically from solar street lighting infrastructure in Johannesburg and Tshwane metropolitan areas during periods of high vandalism and load shedding. The SETS framework and propositions inform understandings where similar structural conditions characterise infrastructure governance: service exclusion creating extraction pressures, spatial inequality concentrating vulnerability, weak co-ordination fragmenting responses, and fiscal constraints limiting implementation options. Transferability to contexts without these conditions requires careful assessment. The framework's emphasis on socio-institutional coupling proves most relevant where infrastructure protection depends on co-ordination capacity that governance architecture struggles to provide.

Chapter 7 translates theoretical insights into practical recommendations addressing institutional co-ordination, community empowerment, resource allocation, and policy integration.

Chapter 7: Conclusions and Recommendations

7.1 Introduction

This chapter synthesises the empirical findings with theoretical framing to explain how solar street lighting resilience in Johannesburg and Tshwane is shaped by interacting social, institutional, and technical dynamics. It answers the research questions directly, draws implications for theory and practice, acknowledges limitations, and proposes directions for further research. The central conclusion is that vulnerability is produced primarily by socio-institutional conditions. Technical specification alone cannot deliver resilience when governance is fragmented, participation is unsafe, and secondary markets create stable demand for stolen components.

7.2 What Has Been Studied and Why This Matters

The study investigated the resilience of solar street lighting subjected to vandalism and theft in two South African metropolitan contexts. It asked why systems intended to avoid copper theft became targets themselves, and what this reveals about urban infrastructure governance. This matters for three reasons. Firstly, street lighting is a public good tied to safety and mobility. Its failure undermines social trust and creates negative perceptions about government capacity (Mugari & Obioha, 2024). Secondly, renewable energy investments form part of broader sustainability strategies aligned with UN Sustainable Development Goals, including SDG 7, SDG 11, and SDG 13 (Agbakwuru et al., 2024). Recurrent vandalism erodes the credibility of these transitions. Thirdly, municipal budgets are constrained. Replacing assets without addressing drivers diverts resources from other essential services.

Vandalism generates a destructive, vicious cycle of ineffectiveness. The loss of functionality leads to perceptions of government inefficiency and incompetence. These perceptions, in turn, increase social alienation between communities and government institutions. This alienation then contributes to further destruction of public assets, as residents who feel

abandoned by the government see little reason to protect infrastructure they perceive as serving an unresponsive system. The cycle perpetuates itself: infrastructure failure reinforces negative perceptions, which fuel disengagement, and this then enables more vandalism, and consequently causes more failures. Breaking this cycle requires understanding not just the physical acts of vandalism but the underlying social contract erosion that enables and perpetuates infrastructure destruction.

The findings show that vandalism emerges from the interaction of economic incentives, spatial opportunity structures, social fragmentation, insider knowledge, and liquid demand for components. These drivers operate through feedback loops. When institutions cannot co-ordinate or respond rapidly, technical hardening is neutralised by adaptive perpetrators. Resilience, therefore, depends on the coupling between technology and governance rather than on device-level specifications.

7.3 What Was the Research Context and Why Does It Matter

Johannesburg and Tshwane are large, diverse cities experiencing rapid urbanisation, inequality, and service delivery constraints. Load shedding has worsened energy insecurity and increased the perceived value of autonomous components such as photovoltaic panels, batteries, and controllers (Mirzania et al., 2023). Deployment sites vary from busy arterial corridors to poorly observed peripheral roads and spaces adjacent to informal settlements.

This context matters because spatial configuration concentrates risk where there is low passive surveillance and easy access. Institutional fragmentation across departments diffuses accountability for prevention, rapid response, and maintenance. Demand-side markets for components make theft economically rational for organised groups and opportunistic actors. Community-state relations are strained in some areas where residents hesitate to report vandalism without protection or visible follow-through (Mamokhere & Meyer, 2022).

The research context matters because these conditions are not unique to Gauteng. Cities across sub-Saharan Africa face similar pressures: rapid urbanisation outpacing governance

capacity, infrastructure investments without corresponding institutional reforms, and communities whose relationship with government has been defined by exclusion rather than partnership. What happens to solar street lights in Johannesburg and Tshwane signals broader challenges for infrastructure resilience across the Global South. These conditions mean that resilience cannot be inferred from technical specifications alone. It depends on governance arrangements and community safety architecture.

7.4 What Was Known and Unknown

Prior South African work documented widespread vandalism of infrastructure and emphasised policing and security responses (Chingozha & Zvokuomba, 2021). Less was known about how social, institutional, and technical factors interact to produce vulnerability in renewable energy assets. Few studies applied socio-technical or resilience frameworks in this specific domain. Empirical accounts from practitioners responsible for planning, operation, and maintenance of solar street lighting were limited.

This study contributes by integrating a social-ecological-technological systems (SETS) perspective (McPhearson et al., 2022) with practitioner evidence to map how drivers, responses, and governance arrangements interact. The SETS framework treats infrastructure as embedded in social and institutional contexts rather than as standalone technical artefacts (Cantelmi et al., 2021).

This study identifies and conceptualises a dynamic of ‘systemic adaptation’: wherein technical substitutions (e.g. from grid-tied to solar) fail to resolve vulnerability because perpetrators adapt within unchanged socio-institutional conditions, thereby reproducing the original failure modes. The SETS framework reveals that the technological dimension (sophisticated hardware) is the dependent variable, whose efficacy is determined by the strength of coupling with the social (community trust) and institutional (governance co-ordination) dimensions. A failure in the institutional dimension effectively neutralises strengths in the technological dimension.

7.5 What Specific Questions Were Answered

This study answered four interconnected questions about solar street lighting vandalism in Johannesburg and Tshwane. First, it identified the key drivers of vandalism: economic incentives, spatial opportunity, social fragmentation, insider knowledge, and secondary markets (RQ1). Second, it evaluated current institutional and technical strategies, revealing critical governance gaps where siloed responsibilities, slow response times, and capital-operational bias undermined technical measures (RQ2). Third, it examined community participation, finding that engagement without safety architecture breeds mistrust rather than protection (RQ3). Fourth, it proposed governance reforms including joint planning mandates, demand-side enforcement, formalised community stewardship, and prevention-oriented budgeting (RQ4). The research adopted an interpretivist qualitative design, conducting thirteen semi-structured interviews with municipal engineers and original equipment manufacturer professionals, analysed thematically using the SETS framework to situate findings across social, institutional, and technical dimensions.

7.6 Findings and Interpretation

7.6.1 RQ1: Drivers of Vandalism

Five drivers recur and reinforce one another.

Economic incentives: Survival appropriation for immediate use, opportunistic monetisation through resale, and heightened demand during load shedding that inflates component prices and multiplies theft incidents.

Spatial opportunity: Vulnerability concentrates where access is easy and observation is weak. Remote arterial corridors and poorly lit or uninhabited zones offer time for organised removal even when devices are hardened.

Social fragmentation: Fear of retaliation and scepticism that reporting vandalism will trigger revenge action, reduces guardianship. Without protected channels and visible response, the willingness to protect assets stays latent.

Insider knowledge: Actors with inside knowledge of specifications, schedules, and monitoring gaps defeat technical measures with relative ease. This is a governance risk more than a design fault.

Secondary markets: Scrapyards, informal traders, and online platforms supply stable demand at low risk, keeping theft profitable.

These drivers are linked in feedback loops. Spatial opportunity converts latent economic incentives into action. Social fragmentation suppresses detection. Insider knowledge improves efficiency. Strong demand guarantees a reward. Technical substitution from grid-tied lighting to solar did not remove these mechanisms but redirected them to new components.

7.6.2 RQ2: Effectiveness of Current Strategies

Municipalities have specified reinforced mounting, tamper-resistant fasteners, elevated placement, and networked monitoring. These measures lower opportunistic attacks but struggle against organised groups who exploit slow response and predictable patrol patterns.

Four governance constraints explain the gap between specification and realised resilience. Siloed responsibilities across energy, roads, safety, and finance produce misaligned plans and unfunded operations. Monitoring without response generates alerts that do not trigger rapid, empowered action on site. Serviceability trade-offs make secure assets hard to maintain, prolonging outages and eroding community trust. Capital-operational bias prioritises installation counts over prevention, monitoring, and maintenance budgets (Mazele & Amoah, 2021).

In short, the gap between specification and performance is not technical. It is institutional. Sensors work. Tamper-resistant bolts work. What does not work is the organisational architecture required to translate technical capability into operational resilience. These findings challenge procurement practices that privilege technical specifications over governance arrangements.

Technical measures sit within institutions that cannot co-ordinate or respond quickly. Capacity remains latent rather than operative.

7.6.3 RQ3: Community Participation and Resilience

Participation is necessary yet not sufficient. Where residents lack safe, anonymous channels and do not see reliable follow-through, engagement efforts yield little protection and may expose individuals to risk. The sequence matters: establish safety architecture first, then mobilise.

Effective participation requires anonymous reporting and whistleblower protections, assured and visible rapid municipal response, clear recognition and defined roles for community structures, and modest but real compensation tied to monitoring effort (Brear & Tsotetsi, 2022). Without these preconditions, participation becomes tokenistic and may increase rather than reduce vulnerability.

7.6.4 RQ4: Governance Changes for Sustainable Management

Four shifts emerged from the analysis.

Joint planning mandates that create cross-departmental accountability, shared budgets, and performance metrics for resilience, including uptime and response time.

Demand-side enforcement that targets scrapyards and online platforms, imposes traceability, and shifts liability onto buyers of undocumented components.

Formalised community stewardship through ward-level arrangements integrated into municipal response protocols, with protections and recognition.

Prevention-oriented budgeting that ties recurrent operational funding to every capital installation and evaluates lifecycle performance rather than installation counts alone (Kapucu et al., 2024).

The proposals are explicitly designed for conditions characterising Global South cities rather than treating them as deficient implementations of Western models. They position infrastructure management as fundamentally political, acknowledging that decisions about deployment, protection, and community participation distribute benefits and burdens while reproducing or challenging existing inequalities. Joint planning addresses the co-ordination failures documented in RQ2. Demand-side enforcement tackles the economic incentives identified in RQ1. Community stewardship responds to the safety prerequisite revealed in RQ3. Prevention budgeting corrects the capital-operational bias that undermines sustained functionality.

These proposals are plausible and align with the diagnosed drivers. They require piloting and comparative evaluation.

7.6.5 Interpreting Through the SETS Framework

As developed in Chapter 6 (Figure 6.4), the SETS framework reveals that infrastructure resilience emerges from integrated socio-technical-institutional arrangements. Social dimensions (community trust, participation), technological dimensions (design robustness, monitoring), and institutional dimensions (governance co-ordination, resources) must function coherently. When any dimension fails, the entire system becomes vulnerable regardless of strengths in other areas.

7.7 How Does This Study Add to the Current Scholarly Debate

The study extends resilience thinking from acute shocks to chronic, system-generated stresses. It documents how technical substitution can reproduce vulnerability when socio-institutional conditions remain unchanged. The contribution is threefold.

Conceptual: It operationalises the SETS perspective in a domain where technocentric solutions have dominated, showing why governance coupling is decisive for resilience. While other scholars have theorised infrastructure as socio-technical (Bibri & Krogstie, 2021), few have empirically mapped how governance fragmentation, community alienation, and technical design interact to produce failure in African urban contexts.

Empirical: It records practitioner evidence for crisis-amplified demand (where load shedding simultaneously justifies solar adoption and elevates vandalism risk), insider threat (where institutional knowledge defeats security measures), and the precondition of safety for participation (where engagement without protection breeds mistrust). These mechanisms are hypothesised in the literature but under-documented in this context.

This study challenges dominant infrastructure resilience literature, which still treats technical robustness as primary and social-institutional factors as context. While scholars like Bibri and Krogstie (2021) theorise smart infrastructure and Cantelmi et al. (2021) review resilience approaches, few empirically demonstrate how governance fragmentation neutralises technical capability in African settings. The crisis-amplified demand mechanism, where load shedding simultaneously justifies solar adoption and elevates vandalism risk, represents a perverse policy feedback loop absent from renewable energy transition literature. Infrastructure problems driving technical substitutions become catalysts, multiplying vulnerability. This has implications beyond South Africa for any context where energy crises motivate distributed generation adoption.

The study reframes vandalism from an enforcement problem to a symptom of governance failures requiring systemic interventions. While conventional approaches treat vandalism as deviant behaviour to be suppressed through surveillance and punishment, the findings

suggest it is rational behaviour enabled by institutional gaps. This shifts the policy response from hardening individual assets to transforming the governance environment that makes theft profitable and low risk. The SETS framework provides the analytical architecture for this reframing, demonstrating that resilience emerges from coupling across dimensions rather than optimising within them.

Methodological: It demonstrates the interpretive value of practitioner interviews for diagnosing socio-technical failure modes and formulating testable propositions for future quantitative work. Municipal engineers and operations managers articulate patterns that quantitative damage assessments miss.

7.8 Practical and Managerial Recommendations

The following recommendations address municipalities, industry partners, and policymakers, responding directly to findings from the research questions.

A. Municipal Coordination Units for Infrastructure Resilience (RQ2, RQ4)

Establish dedicated coordination units under the city managers to convene energy, roads, safety, and finance departments. Implement shared budgets, unified performance metrics for response time and uptime, and pilot programmes in high-risk wards with quarterly reviews. This addresses governance fragmentation identified as a critical resilience barrier.

B. Rapid Response Paired with Monitoring (RQ2)

Convert sensor alerts into graded on-site responses within defined time targets. Visible municipal action deters repeat attacks and builds community trust, even where arrests remain unlikely. Prioritise rapid system restoration alongside investigation to maintain service continuity.

C. Demand-Side Disruption (RQ1, RQ4)

Licence scrapyards with mandatory transaction registries and implement surprise inspections. Monitor online trading platforms and create buyer liability for undocumented

components. Publish enforcement outcomes regularly. This disrupts secondary markets that enable theft monetisation.

D. Safety-First Community Stewardship (RQ3)

Launch anonymous reporting channels integrated with ward committees and neighbourhood structures. Provide training, recognition, and codified protections for community reporters. Address fear-based non-reporting by ensuring reporter safety and demonstrating responsive action.

E. Budget Reforms for Prevention (RQ2, RQ4)

Ring-fence operations and maintenance allocations with each new installation. Assess lifecycle performance rather than installation numbers. Align contractor incentives and municipal recognition with sustained functionality, shifting focus from capital expenditure to operational resilience.

F. OEM Design for Maintainability Under Constraint (RQ2)

Standardise components, design modular systems, and simplify authorised access procedures. Enable rapid, safe maintenance without undermining security features. Reduce dependence on specialised tools or proprietary parts that delay repairs in resource-constrained environments.

G. Performance-Based Service Partnerships (RQ2)

Transition from install-and-exit models to uptime-linked contracts. Build local maintenance capacity, share risk in high-exposure corridors, and tie payment to sustained system performance. This aligns OEM incentives with long-term resilience rather than deployment volume.

H. National Learning and Standards (RQ4)

Establish inter-municipal platforms to compare pilot outcomes and share effective practices. Publish procurement guidance integrating security, maintainability, and community engagement. Develop minimum national standards for component traceability and verification to support demand-side disruption efforts.

Each recommendation addresses specific failure modes identified in the findings. Co-ordination units solve the siloed responsibilities problem where energy deploys, roads are maintained, safety responds, and finance controls budgets with no integration. Rapid response converts monitoring data into deterrence by demonstrating state capacity. Demand-side enforcement removes the economic rationality of theft by increasing risk and reducing reward. Safety-first stewardship acknowledges that communities cannot protect what makes them targets. Prevention budgeting corrects the political economy that rewards installation counts over sustained functionality. These are not wish-list reforms. They are achievable within existing budgets if governance priorities shift.

The recommendations privilege co-ordination and prevention over punishment and replacement. This represents a fundamental shift from reactive to proactive infrastructure management. Municipalities currently spend resources replacing stolen components and investigating thefts. Redirecting a fraction of these resources to prevention mechanisms (anonymous reporting channels, rapid response protocols, scrapyard monitoring) generates better outcomes at lower lifecycle cost.

Implementation sequencing matters. Recommendations A and D (co-ordination units and safety-first stewardship) create the governance preconditions for effectiveness of B, E, and F (rapid response, prevention budgets, maintainable design). Recommendation C (demand-side disruption) operates independently and can proceed in parallel. Municipalities should not wait for perfect co-ordination before acting on market disruption, but community mobilisation without safety architecture will backfire.

These recommendations are plausible within existing resource envelopes if priorities shift from deployment theatrics to operational effectiveness.

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7.9 Recommendations for Future Research

Five research directions would advance understanding and improve practice.

- Centre community voices: Use participatory and ethnographic methods so residents co-define questions, outcomes, and evaluation metrics. Examine ownership, safety, legitimacy, and the conditions for protective behaviour.
- Quantitatively test qualitative claims: Map incidents against hypothesised risk factors. Correlate theft rates with load shedding intensity. Compare intervention cost-effectiveness. Analyse investigation records for insider involvement.
- Study positive deviance: Identify corridors or cities with lower vandalism rates. Compare governance structures, budgets, specifications, and engagement models to isolate resilience factors.
- Pilot and evaluate the integrated framework: Co-design municipal pilots that combine recommendations A through E. Evaluate against matched comparison areas using uptime, response time, attack frequency, and lifecycle cost metrics.
- Extend beyond street lighting: Test whether the same systemic adaptation dynamic appears in water, sanitation, metering, transport signalling, and distributed generation.

These research directions move from description to explanation to intervention evaluation. They build progressively toward infrastructure governance models that work in contexts characterised by constraint rather than treating constraint as a temporary deviation from normality. The framework's emphasis on socio-institutional coupling proves most relevant where infrastructure protection depends on co-ordination capacity that governance architecture struggles to provide.

7.10 Conclusion

The study shows that technical substitutions, such as moving from grid-tied to solar street lighting, do not resolve vulnerability when the surrounding socio-institutional system remains unchanged. Economic incentives, spatial opportunity, social fragmentation, insider knowledge, and liquid secondary markets generate predictable attack patterns. When monitoring is not paired with rapid response, when budgeting favours installations over operations, and when participation is sought without prior safety guarantees, resilience claims do not materialise.

Resilience requires governance architecture: joint planning mandates, prevention-oriented finance, demand-side regulation, and safety-first community stewardship. These changes are less about new money than about how existing resources are co-ordinated and held to account. Municipalities that act on these insights can improve uptime, reduce recurrent replacement costs, and restore confidence that public infrastructure will be protected and maintained.

The findings have transferability beyond solar street lighting. The systemic adaptation dynamic, where technical substitutions reproduce rather than resolve vulnerability, likely appears across infrastructure domains in contexts characterised by governance fragmentation, social exclusion, and profitable secondary markets. Water infrastructure, sanitation systems, smart metering, traffic management, and distributed generation all face similar pressures. If the pattern holds, it suggests that Global South cities need fundamentally different infrastructure governance models rather than incremental improvements to existing approaches.

This study demonstrates that infrastructure resilience in resource-constrained contexts cannot be purchased through technical upgrades alone. It must be built through governance reforms that align institutional incentives, empower community stewardship, and disrupt the economic logic of theft. Solar street lighting can succeed in South African cities, but only if municipalities abandon the fiction that vandalism is a crime problem solvable through better locks and more cameras. It is a governance problem requiring institutional transformation.

The stakes are high. South African cities stand at a crossroads. They can continue current practices, replacing stolen components indefinitely while wondering why communities do not take ownership. Or they can recognise that technical substitutions without governance transformation predictably fail. The evidence presented here suggests the latter path is necessary. Municipalities that acknowledge this reality and act accordingly will protect their investments, restore service reliability, and rebuild the social contract that makes infrastructure protection possible.

The intellectual task ahead is to refine and test these propositions. The practical task is to pilot, measure, and learn. Both are necessary if renewable infrastructure is to deliver on its promise in South African cities.

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Appendix A

Interview Guide: Infrastructure Resilience and Vandalism (Solar Streetlighting in Selected Gauteng Metros)

Context and Role

M1. Please describe your connection to streetlighting in this area. How long have you lived or worked here, and in what capacity?

M2. Which places do you know best regarding streetlighting in this area? If you know areas with solar units, please mention them.

RQ1: Drivers and Patterns (solar lens)

1. From what you have seen or heard, what are the main reasons solar streetlights are damaged or stolen in your area?

Probes if known: where and when it tends to happen; which parts are usually targeted; any triggers or routines that stand out; a recent example in the last twelve months.

2. Thinking about streetlighting in general, what factors make an installation vulnerable here, and what would that imply for solar units?

RQ2: Responses and Effectiveness

3. What actions have you seen taken to prevent or reduce vandalism or theft of solar streetlights?

Probes if known: technical measures such as cages or fasteners; patrols; reporting channels; response times; what changed afterwards; any unintended effects.

4. Which measures used for streetlighting in general would work for solar units here, and which would not? Please explain.

RQ3: Community Participation

5. In what ways have residents, leaders or local groups taken part in protecting or maintaining streetlighting in your area? What has this meant for solar units, where present?

Probes if known: ward committees; community policing forums; messaging groups; neighbourhood watches; what helps people get involved; what gets in the way.

RQ4: Governance and Policy

6. What would need to change in organisation or policy to protect solar streetlighting better in places like this?

Recommendations

7. If you could recommend three actions that would make the biggest difference here for solar streetlighting, what would they be, and why?
8. Is there anything important we have not covered that would help explain why vandalism happens or how it can be reduced?

Appendix B

Informed Consent

Participant information

Study: Infrastructure Resilience and Vandalism: Solar Streetlighting in Selected Gauteng Metros.

Researcher: Thabo Metsing (GIBS MBA, Gordon Institute of Business Science (GIBS), University of Pretoria) | Email: 23992485@mygibs.co.za | Mobile: 071 602 0302

Supervisor: Prof Richard Meissner (Gordon Institute of Business Science (GIBS), University of Pretoria) | Email: meissr@unisa.ac.za | Mobile: 071 677 6262

Purpose: To understand professional and community experiences with solar streetlighting in vandalism-prone contexts.

What participation involves: A single interview of approximately 45–60 minutes, online or in person, audio recorded through teams or similar software package only with your permission.

Voluntary participation: Participation is entirely voluntary; you may skip any question and may withdraw at any time without negative consequences.

Confidentiality and anonymity: Your name, role and employer will not appear in transcripts or reports. Pseudonyms will be used; indirect identifiers will be removed.

Data handling: Audio and transcripts will be stored on a password-protected google-drive accessible only to the researcher and supervisor; retained for 10 years and then securely destroyed.

Risks/benefits: Minimal foreseeable risk; you may skip any topic that causes discomfort. There are no direct personal benefits, though findings may inform improved protection of public assets.

Queries: Contact the researcher or supervisor on the details above.

Consent (please tick and sign)

- ☐ I have read and understood the information above and was able to ask questions.
- ☐ I understand that my participation is voluntary and that I may withdraw at any time.
- ☐ I consent to take part in this interview.
- ☐ I consent / do not consent (delete one) to audio recording of the interview.

Participant name: _____ Signature: _____

Date: ____/____/____

Researcher name: _____

Signature: _____

Date: ____/____/____

Appendix C

EDITOR CONFIDENTIALITY & NON-DISCLOSURE AGREEMENT

(POPIA-Compliant)

Study: Infrastructure Resilience and Vandalism: Solar Streetlighting in Selected Gauteng Metros

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APPENDIX D

Thematic Analysis Codebook

This appendix documents the complete coding framework developed through thematic analysis of 13 semi-structured interviews. The codebook contains 30 codes organized into five parent categories aligned with the study's research questions and SETS framework. Codes were developed iteratively, with saturation achieved by Interview 7. Analysis tracked both the density of coded segments (groundedness) and the prevalence of themes across participant transcripts.

Table D1: Driver Categories and Participant Frequency

Driver Category	Frequency (n)	Prevalence	Key Sub-themes
Economic Incentives and Material Value	13/13	Universal	Survival theft; Opportunistic criminality; Crisis-amplified demand
Spatial Vulnerability	12/13	Nearly universal	Proximity to informal settlements; Physical accessibility; Remote locations
Social Fragmentation	11/13	Majority	Fear-based non-reporting; Institutional capture; Passive acceptance
Secondary Market Infrastructure	10/13	Majority	Unregulated scrapyards; Lack of verification; Demand-side enablers
Insider Vulnerabilities	9/13	Substantial	Direct employee theft; Information leakage; Procurement corruption
OVERALL PATTERN	13/13	Universal	All participants identified multiple drivers as interconnected

Note: Frequencies show theme prevalence across n=13 participants. Qualitative descriptors: Universal (all/nearly all participants); Majority (eight or more participants); Substantial (six to seven participants); Some (four to five participants).

participants); Few (two to three participants). These frequencies provide transparency about pattern strength without implying statistical generalisability.

Table D2: Research Question Coverage Summary

Research Question	Groundedness	Share (%)
RQ1	323	31.9%
RQ2	262	25.9%
RQ3	217	21.4%
RQ4	210	20.8%
Total	1,012	100%

Note: Groundedness refers to the total number of text segments coded under each research question. The balanced distribution across research questions indicates comprehensive analytical attention to all study objectives.

Table D3: Code Saturation Pattern

Interview	Participant	New Codes	Codes Emerged	Cumulative
1	P1	18	C01-C02, C05-C06, C10, C13-C15, C18-C19, C21-C22, C24-C26, C28-C30	18
2	P2	5	C08, C12, C16, C23, C27	23
3	P3	5	C04, C07, C09, C17, C20	28
4-6	P4-P6	1	C11 (Interview 6)	29
7	P7	1	C03	30
8-13	P8-P13	0	No new codes emerged	30

Note: Theoretical saturation was achieved by Interview 7, with no new codes emerging in the final six interviews. This pattern demonstrates sufficient sample size and robust thematic coverage.

Table D4: Complete Codebook

RQ1: Key Drivers of Vandalism

Parent Category: Vandalism Drivers

Code ID	Code Name	n	Definition
C01	Material Theft Resale	92	Theft for resale/scrap market value (panels, batteries, cabling).
C02	Theft Private Use	42	Theft to power private homes/informal sites (non-commercial use).
C03	Unemployment Poverty	20	References to unemployment/poverty as enabling drivers of theft.
C04	Load Shedding Impact	41	Load-shedding and unreliable supply increasing incentives/opportunities for theft.
C05	Crime Facilitation	39	Intentional disabling of lights to facilitate crime (preferring darkness).
C06	Insider Collusion	36	Offending enabled by insiders/contractors/temporary workers with system knowledge.
C07	Scrap Dealer Network	14	Mentions of scrapyards/scrap dealers receiving stolen components.
C08	Design Visibility	37	Risk arising from high visibility/easy access of components (panel, battery).
C09	Community Disconnect	2	Low social cohesion/weak community ties reducing informal guardianship.

RQ2: Institutional and Technical Response Effectiveness

Parent Category: Technical Responses

Code ID	Code Name	n	Definition
C10	Tamper Proof Design	23	Design choices to resist tampering (reinforced housings, anti-tamper fasteners).
C11	Fencing Access Control	8	Perimeter barriers and controlled access (fencing, spikes, barbed wire).
C12	Asset Marking Traceability	24	Marking/ID/tracking of assets to deter and trace theft.
C13	Telemetry Monitoring	48	Remote monitoring/telemetry/LMS/early-detection and alerts.
C14	Continuous Lighting	18	Keeping lights on/energised as a deterrent practice.

Parent Category: Institutional Responses

Code ID	Code Name	n	Definition
C15	Security Patrols	69	Security patrols/response teams (public or private).
C16	Legal Prosecution	25	Prosecution/legal action/by-laws to deter theft and vandalism.
C17	Cable Theft Unit	47	Dedicated units focused on cable/electricity infrastructure theft.

RQ3: Community Participation Dynamics

Parent Category: Community Participation

Code ID	Code Name	n	Definition
C18	Community Policing Forums	11	Community policing forums/CPF involvement.

Code ID	Code Name	n	Definition
C19	Community Reporting	71	Public reporting channels (WhatsApp, call centres, social media).
C20	Community Handover Events	10	Formal handover/donation ceremonies/events signalling local custodianship.
C21	Awareness Campaigns	50	Awareness and education campaigns for public vigilance and stewardship.
C22	Community Ownership	32	Statements of local ownership/stewardship/custodianship.
C23	Community Donations	16	Donations/sponsorships of lights/materials by residents/businesses.
C24	Community Maintenance	27	Community-supported maintenance/repairs/monitoring routines.

RQ4: Governance Requirements

Parent Category: Governance Changes

Code ID	Code Name	n	Definition
C25	Policy Frameworks	25	Policies/standards/by-laws/frameworks enabling protection.
C26	Coordination Gaps	17	Breakdowns in coordination across City, police, private security, communities.
C27	Stakeholder Collaboration	12	Evidence of coordinated, multi-stakeholder collaboration.
C28	Weak Enforcement	90	Ineffective/absent enforcement or policing capacity.

Code ID	Code Name	n	Definition
C29	Budget Constraints	32	Budget/funding constraints affecting deployment or protection.
C30	Maintenance Protocols	34	Maintenance schedules, spares planning, and procedures for O&M.

APPENDIX E

Participant Characteristics

Participant	Role	Organisation	Experience in street lighting (years)	City	Gender
P1	Engineer	Municipal	15	JHB	F
P2	Engineer	Municipal	22	TSHWANE	M
P3	Engineer	Municipal	18	JHB	F
P4	Engineer	Municipal	20	TSHWANE	M
P5	Engineer	Municipal	12	JHB	F
P6	Engineer	Municipal	14	TSHWANE	M
P7	Engineer	Municipal	25	JHB	F
P8	Engineer	Municipal	16	TSHWANE	M
P9	Engineer	Municipal	19	JHB	F
P10	Professional	OEM	10	JHB	M
P11	Professional	OEM	8	TSHWANE	M
P12	Professional	OEM	5	JHB	M
P13	Professional	OEM	30	TSHWANE	M
TOTAL	9 Municipal 4 OEM		Mean: 16.5 Range: 5-30	7 JHB 6 TSH	5 F 8 M

Note: Experience ranges from five to 30 years, with a mean of 16.5 years

RQ (verbatim)	Core constructs & theoretical lenses	Data sources used	Analysis methods	Key findings & theoretical contributions aligned to RQ	Where discussed	Gaps & future research
RQ1: What are the key drivers of vandalism affecting solar streetlighting in Johannesburg and Tshwane?	SETS interdependencies; socio-economic stressors; crime/opportunism; asset protection; informal connections; extraction pressures; spatial inequality (Sharifi et al., 2023; Kim et al., 2022; Östh et al., 2018; Liu et al., 2022).	Primary: 13 interviews (5 municipal engineers, 4 OEMs, 4 community stakeholders) Secondary: City of Johannesburg IAR 2023/24; City of Tshwane AR 2023/24; AGSA MFMA 2022/23; City Power 2025/26 MTREF.	Inductive thematic analysis; documentary content analysis; pattern matching across stakeholder categories.	Evidence: Theft, illegal connections, and vandalism are persistent drivers amplified by socio-economic conditions and weak enforcement. Theoretical Contribution: Identified "systemic adaptation" dynamic—technological substitution (grid to solar) displaces rather than resolves vulnerability when socio-institutional conditions remain unchanged. Service exclusion creates extraction pressures in reinforcing feedback loop. Quantified: All 13 participants identified material theft; 9/13 noted theft for private use; 11/13 emphasized socio-economic drivers.	Theme 1, Section 5.1.2; Discussion Section 6.2; Propositions 1-2 in Section 6.2	Solar-component-specific theft quantification limited in official documents (interviews provide rich detail). Future research: Longitudinal tracking of systemic adaptation patterns; comparative analysis across multiple African cities.
RQ2: How effective are current institutional and technical strategies in preventing solar infrastructure vandalism?	Tech fixes vs. socio-technical resilience; path dependency; O&M capacity; governance coordination; CAPEX-OPEX mismatch; institutional fragmentation (Helmrich et al., 2023; Chang et al., 2021; Kim et al., 2022; Sharifi et al., 2023).	Primary: 13 interviews Secondary: AGSA MFMA 2022/23; City Power 2025/26 MTREF; CoJ IAR 2023/24; Tshwane AR 2023/24.	Thematic analysis with deductive sensitization from SETS framework; cross-source pattern matching; documentary validation.	Evidence: Technical fixes alone underperform without governance coordination, sustained O&M funding, and protection measures. Recurrent losses reflect fragmented institutional responses. Theoretical Contribution: Technological dimension efficacy is dependent variable determined by coupling strength with social (community trust) and institutional (governance) dimensions. Identified CAPEX-OPEX mismatch as systematic constraint. Quantified: 12/13 participants noted coordination failures; 10/13 emphasized maintenance funding gaps; 8/13 described sophisticated tech undermined by institutional weakness.	Theme 2, Section 5.1.3; Discussion Section 6.3; Recommendations Section 7.10.2-7.10.3	Limited before-after quantified metrics for specific countermeasures in official reports. Future research: Controlled comparison of resilience outcomes across different governance arrangements; lifecycle cost-benefit analysis of integrated vs. siloed interventions.

RQ3: How does community participation impact the resilience of solar streetlighting?	Co-production; social capital; trust; social licence; reporting/rapid response; enabling conditions for participation; awareness-action gap (Brear & Tsotetsi, 2021; Tyhotyholo & Ncube, 2023; Liu et al., 2022; Van Koppen et al., 2024).	Primary: 13 interviews Secondary: CoJ IAR 2023/24 (community partnerships); Tshwane enforcement operations documentation.	Thematic analysis examining enabling conditions; documentary corroboration of partnership effectiveness; cross-case pattern identification.	Evidence: Community partnerships and reporting reduce exposure locally when enabling conditions present. However, fear, timing barriers, role ambiguity, and structural capture limit effectiveness. Theoretical Contribution: Identified "awareness-action gap"—communities understand infrastructure value but cannot act without institutional safety mechanisms and legitimate participation pathways. Community participation functions as amplifier (when enabled) or accelerator of degradation (when absent). Quantified: All 13 participants acknowledged participation potential; only 4/13 (P1, P9, P12, P13) described sustained protective behavior; 7/9 contexts with trusted leadership showed effective participation vs. 1/9 without.	Theme 3, Section 5.1.4; Discussion Section 6.4; Table 5.7 (participation enabling conditions); Recommendations Section 7.10.4	Systematic KPIs for community-based interventions largely absent in official municipal reporting. Quantitative measurement of participation effectiveness limited. Future research: Development and testing of community participation metrics; longitudinal analysis of participation sustainability; comparative analysis of formalized vs. informal participation structures.
RQ4: What governance changes can promote sustainable solar infrastructure management in vandalism-prone areas?	Institutional capacity; procurement/contracting; inter-organizational coordination; resilient systems integration; SETS coupling requirements; formalized co-stewardship; resource ring-fencing (Kim et al., 2022; Sharifi et al., 2023; Cantelmi et al., 2021).	Primary: 13 interviews Secondary: AGSA MFMA 2022/23; City Power 2025/26 MTREF; CoJ & Tshwane ARs 2023/24; Green Pages requirements.	Thematic synthesis of reform recommendations; documentary validation of institutional constraints; pattern analysis across stakeholder categories.	Evidence: Needed shifts include tightened SCM/contract management; ring-fenced O&M budgets; integrated loss-reduction planning; formalized community co-stewardship; demand-side interventions (scrapyard regulation). Theoretical Contribution: Framework positioning infrastructure management as fundamentally political—distributing benefits/burdens and reproducing/challenging inequalities. Governance architecture must enable	Theme 4, Section 5.1.5; Discussion Section 6.5; Propositions 3-4 in Section 6.5; Comprehensive recommendations Chapter 7, Sections 7.10.1-7.10.5	Implementation timelines, costed roadmaps, and political feasibility analysis are prospective rather than empirical. Future research: Action research testing governance reforms; comparative policy analysis across metros; political economy analysis of reform implementation barriers.

				coordination across fragmented organizations; institutional safety mechanisms must support community engagement. Quantified: 13/13 participants identified governance coordination as critical need; 11/13 emphasized O&M ring-fencing; 9/13 called for formalized community roles; 8/13 noted demand-side intervention gap.		
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APPENDIX F

Consistency Matrix

The alignment matrix is grounded in the Chapter 2 framing literature. Social–ecological–technological systems (SETS) scholarship emphasises coupled interdependencies in urban infrastructure (Sharifi et al., 2023; Kim et al., 2022). Within this lens, resilience depends not only on technical design but also on governance capacity, maintenance regimes, and community co-production (Helmrich et al., 2023; Chang et al., 2021). Social capital and participation shape stewardship, reporting, and rapid response to vandalism, thereby influencing infrastructure outcomes (Östh et al., 2018; Liu et al., 2022; Brear & Tsotetsi, 2021; Tyhotyholo & Ncube, 2023). These constructs frame the research questions (RQs) and inform the triangulated interpretation of findings in Chapters 5–7.

Notes

- Evidence strength:** Based on triangulation between 13 semi-structured interviews, member checking with 5 participants, and corroboration with official documents.
- Secondary documents:** Auditor-General South Africa (AGSA) MFMA General Report 2022/23; City of Johannesburg Integrated Annual Report 2023/24; City of Tshwane Consolidated Annual Report 2023/24; City Power MTREF/Budget 2025/26.
- Abbreviations:** SETS (Social-Ecological-Technological Systems); O&M (Operations & Maintenance); SCM (Supply Chain Management); KPI (Key Performance Indicator); CPF (Community Policing Forum)

APPENDIX G

Interviewee Profiles

Pseudoname	Expirience years in streetlighting	Resident in	Proffession	Gender
Participant 1	10	Tshwane	Municipal Engineer	Female
Participant 2	20	Tshwane	Municipal Engineer	Male
Participant 3	8	Tshwane	Municipal Engineer	Male
Participant 4	10	Tshwane	Municipal Engineer	Female
Participant 5	15	Johannesburg	Municipal Engineer	Female
Participant 6	10	Johannesburg	Municipal Engineer	Female
Participant 7	24	Johannesburg	Municipal Engineer	Male
Participant 8	5	Johannesburg	OEM Engineer	Male
Participant 9	20	Tshwane	Streetlighting OEM Sales	Male
Participant 10	30	Johannesburg	Streetlighting OEM Sales	Male
Participant 11	25	Johannesburg	Municipal Engineer	Female
Participant 12	20	Johannesburg	Streetlighting OEM Sales	Male
Participant 13	20	Johannesburg	Municipal Engineer	Male

APPENDIX H

Editor's Letter



15 October 2025

To whom it may concern,

This is to certify that I have edited Thabo Metsing's research report titled **Infrastructure Resilience against Vandalism: A Case Study of Solar Street Lighting in Selected Gauteng Metros**, ethically and to the best of my ability, checking the grammar, spelling, punctuation, tense and sentence construction, as well as repetition/redundancy of sentences, but not content.

I formatted the document according to the document titled Green Pages 2025 Modular and Part-time groups_Final.

I checked the references for spelling, punctuation, format and spacing and added any missing information.

The student had the ability and choice to accept or reject my suggestions and changes. Detecting plagiarism is not part of my scope, and it is the author's responsibility to avoid plagiarism.

I wish him the best of luck.

Yours sincerely,

Bridget LötZ

