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System Dynamics in Energy Transitions: Understanding Complexity and Driving Engagement

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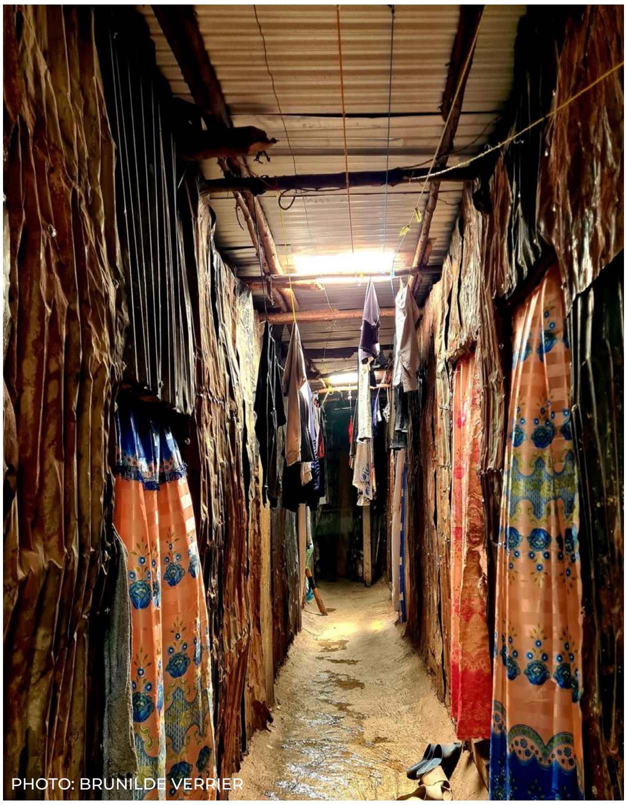
Summary

Energy transitions take place within deeply interconnected systems. System Dynamics (SD) is a modelling approach grounded in systems thinking principles that account for complexity and stakeholder diversity. It offers several opportunities that are particularly relevant in low- and middle-income countries (LMICs).

Key advantages

- **Unconstrained thinking:** SD encourages decision-making to go beyond what is easily measurable. Relying only on data that are readily available and easily quantifiable risks overlooking other essential influences on policy design and its outcomes.
- **Nuanced understanding:** The approach offers a fuller picture of complex problems by integrating both qualitative and quantitative tools.
- **Dynamic perspective:** By moving beyond static assumptions, SD can explore how changes in systems evolve over time.
- **Growing interest and proven relevance:** The use of SD has shown promising results in LMICs, being applied to the energy–water–food nexus and increasingly to critical minerals use. More studies are needed to integrate Gender Equality and Social Inclusion (GESI) considerations.
- **Systems mindset:** SD helps with the recognition of patterns, feedback loops, and interdependencies. This approach can foster a wider systems-oriented perspective.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Electricity supply into informal settlements.

Systems approaches can complement traditional modelling and enrich understanding across sectors and disciplines, notably between industry, academia, and policy. Hybrid studies combining SD with conventional methods are likely to influence future modelling practices and contribute to the strategic integration of energy transitions, energy security, and sustainable development. This brief introduces the core concepts of SD as a tool for understanding complex systems.

Introduction

Systems-based approaches are gaining traction as a way to integrate socio-political, socio-economic, and techno-economic considerations and enable collaborative and fair practices in sustainable transitions [1]. For instance, rules and structures in society can create power struggles, disagreements between stakeholders, and resistance to change [2], all of which can delay or reduce the effectiveness of policy interventions or development projects. Similarly, complex issues are perceived and experienced differently by different stakeholders, which can create confusion and controversy around climate policy decisions [3]. This brief introduces the core concepts of Systems Dynamics (SD) – an established systems thinking modelling methodology – and highlights its value in bridging sectors and disciplines to better understand the behaviour of complex systems. In the context of low- and middle-income countries (LMICs), SD supports the design of more inclusive and resilient interventions, while offering the possibility to integrate both qualitative and quantitative approaches.

What is a System and why System Dynamics?

A system is a set of interconnected elements that forms a structure to produce a series of events over time, known as system behaviour [4]. In energy and transport, the term systems typically refers to the techno-economic infrastructures and processes involved in energy generation, distribution, and consumption, while analyses of such systems often focus on outcomes (ie behaviours), such as balancing supply and demand and reducing carbon emissions. However, a system is more than the sum of its parts, and its behaviour will be influenced by flows, interconnections, accumulations, and delays, as well as by the diverse ways in which different actors perceive the system (ie their mental models: see **Box 1**). There is also increasing recognition that these systems are socio-technical by nature. This means that they are deeply embedded within, and influenced by, social and institutional structures which each have their own dynamics. For instance, a common behaviour in socio-technical systems is policy resistance, where efforts to improve outcomes are undermined by unintended consequences that were not fully anticipated during the planning of interventions due to the complexity of the broader system. Policy resistance arises from tensions between the objectives of different actors, each operating according to their own rules and purposes. These dynamics contribute to the system's self-organising capability, where existing structures and behaviours tend to persist. This persistence reinforces system inertia—resistance to change—which can significantly influence both the pace and direction of transitions. Traditional modelling approaches, which focus on cost-optimising parameters, can often overlook the dynamic, non-linear, and time-dependant nature of systems, and how they are affected by human perceptions.

SD is a modelling approach developed at MIT in the 1960s, which aims to overcome some of the above limitations. Initially applied to industrial systems, it was later applied to urban dynamics and to environmental resources management (World Dynamics & The Limits to Growth)[5] [6]. SD is dedicated to understanding the nature, structure, and interconnectivity of systems, in order to avoid unintended consequences. It provides a flexible methodological environment comprising qualitative and quantitative systems mapping tools such as Causal Loop Diagrams and Stock and Flow models. These are described in more detail below.

Two notable features of SD compared to traditional modelling approaches are: 1) the consideration of the inherent properties of systems, namely their interconnectedness, feedback mechanisms, and delays; and 2) the incorporation of the system effects of human perceptions and behaviours. System dynamics is about understanding *how complex systems behave* and why this brings about unintended consequences. *In essence, thinking in systems requires a shift towards a more holistic and 'circular' vision—one informed by feedback loops—of how complex issues unfold over time.* Because of this focus on feedback mechanisms and revealing the structure of systems to understand their behaviour, the approach is adaptable to any sector and system, as long as a clear purpose and appropriate boundaries are set to provide usable results on a specific issue.

One of the important aspects of this perspective is the acknowledgement that human decisions are based on implicit individual or collective decision-making rules, and that perceptions often differ from actual conditions. This can be due to an accumulation of delays (eg measurements, reporting) along energy supply chains or agency departments, but also due to personal beliefs and individual experiences. Unveiling the assumptions and rules that lead to decision-making is crucial, because these can be at the root of unintended consequences arising later and in other areas of the system. For instance, taxes on energy for transport, heating, and cooking that ignore local needs, stakeholder views, and implementation challenges may lead to bottlenecks and confusion across the system, leading to undesirable outcomes for all.

SYSTEMS CONCEPT: MENTAL MODELS

Mental models are the perceptions and accumulated personal experiences that shape our understanding of the world. They influence our analysis of the present and our predictions for the future. Unveiling different actors' assumptions about a system or how problems are perceived differently by several stakeholders is essential, not only for participation and inclusion, but also because these assumptions affect human behaviours and decision-making outcomes. As a result, they may have an important effect on the behaviour of systems. Decisions around energy use and technology adoption are shaped by bounded rationality (human knowledge and capabilities are imperfect), psychological factors, and emotional responses [7]. These factors are underrepresented in optimisation models, which tend to prioritise rational cost-benefit analyses over behavioural complexity [8].

A Problem-Based Approach to Modelling

Defining a problem in collaboration with stakeholders, or through insights drawn from literature, helps establish the central focus and boundaries of SD modelling or mapping efforts. SD uses both qualitative and quantitative approaches, which are often complementary, but can also be used as standalone efforts. The main qualitative modelling tool used in SD is called a Causal Loop Diagram (CLD). Its quantified equivalent, designed for computer simulation, is the Stock and Flow Diagram (SFD), commonly known as a system dynamics model.

Qualitative systems mapping with CLDs

CLDs highlight interconnections between systems elements and the structure they form. For instance, there is a direct causality between energy technology costs and technology adoption. However, the rate of adoption is also likely to influence cost fluctuations, so instead of a single causality this is also a feedback structure. CLDs aim to unpack the interconnected feedback effects which reinforce specific situations. They are also helpful in facilitating communication and engagement around solutions. Such qualitative systems mapping offers valuable insights and can be effectively used alongside any type of modelling approach.

CLDs can also highlight the tensions between different stakeholder needs and perceptions. For instance, misunderstandings between companies and communities can be captured by including variables representing levels of trust and engagement.

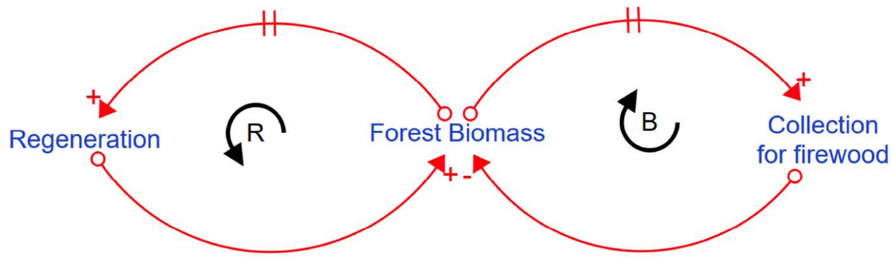
This process is best undertaken using participatory approaches but can also be informed by using best available data, including findings from literature and document analysis. In systems thinking, relying on the best estimations available in order to capture as many influencing factors as possible is always preferable to overlooking or ignoring those intangible factors that are difficult to quantify.

To create a CLD, the following steps are followed:

- Definition and formulation of the problem(s)
- Identification of key variables
- Drawing of behaviour over time (BOT) graphs of the expected, feared, and desired evolution of variables over the time horizon of interest
- Mapping causalities between each variable (ie how changes in one element affect other elements), and
- Closing the loops to reveal feedback mechanisms, in a continuous improvement process.

Policy solutions and levers of change can also be explored and represented in CLDs as external variables that may influence the behaviour and dominance of feedback loops. **Figure 1** provides an example of a simple CLD, while a more complex diagram is given in **Box 2**.

***Figure 1:** Hypothetical CLD showing a simple reinforcing and balancing loop influencing the availability of biomass from forests*



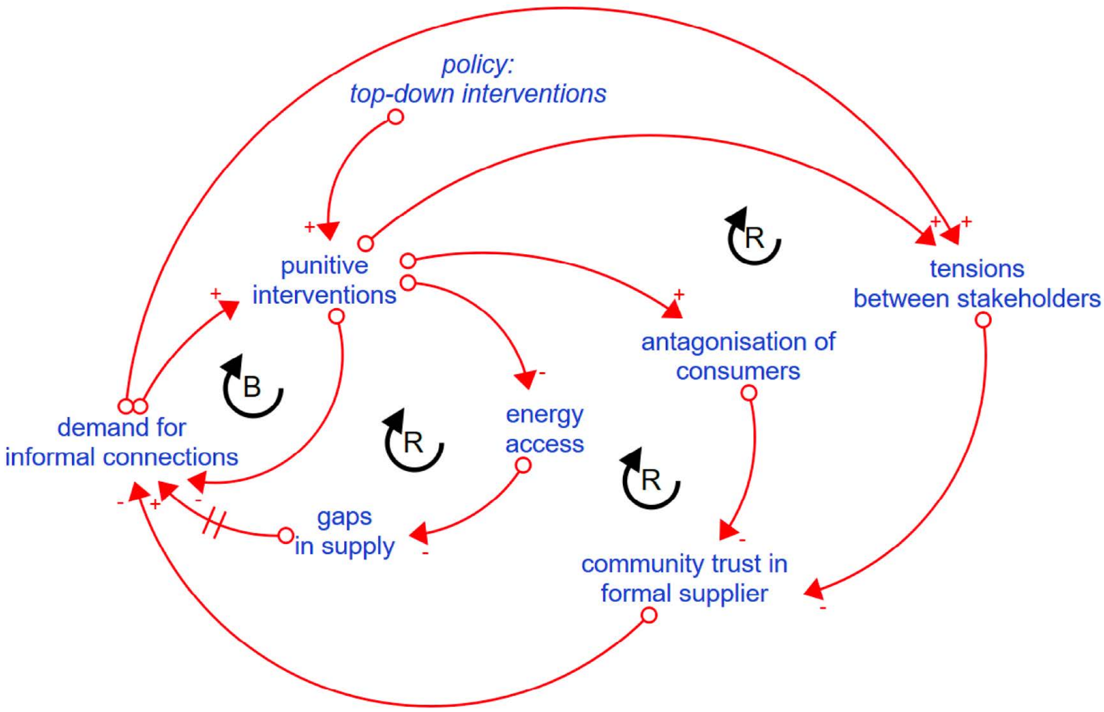
How to read a CLD: ⁺ a causal link where a change in variable V1 causes a change in variable V2 in the same direction: eg larger amounts of available forest biomass lead to larger amounts of wood collection, and lower amounts of available forest biomass lead to lower amounts of wood collection. ⁻ a causal link where a change in V1 causes a change in V2 in the opposite direction: eg more biomass collection reduces the amount of forest biomass still available, and less biomass collection leads to a higher amount of forest biomass still being available. Ⓡ represents a reinforcing feedback loop, amplifying change: eg higher amounts of forest biomass lead to more regeneration, which in turn increase the amount of forest biomass available. Ⓑ represents a balancing feedback loop, seeking equilibrium. These loops feature an odd number of ⁻ causal links. || is a delay mark.

A thorough qualitative CLD may be sufficient to spread awareness about system interconnections and unlock problematic situations. It is also possible to complete the study with the creation of a quantitative simulation model, as described in the next section. This enables scenario simulation (eg understand the evolution of the impact of a policy over time), the integration of random shocks (eg weather events or pollution incidents), sensitivity analyses, and the creation of user interfaces.

CLD EXAMPLE: UNINTENDED CONSEQUENCES IN KENYA'S INFORMAL SETTLEMENTS

Communities in informal settlements require affordable and reliable access to energy to meet their essential needs. While the national utility provider aims to expand access to formal electricity services, tensions persist with informal electricity suppliers who offer affordable prices and more flexible payment options to households and businesses in the settlement [9]. One important reinforcing mechanism at play is that top-down interventions intended to curb demand for informal electricity by restricting access often backfire. These measures create supply gaps, antagonise formal customers, and foster resentment between stakeholders, ultimately reinforcing strong community support for informal providers [10]. These dynamics are illustrated in **Figure 2**.

***Figure 2:** Top-down, punitive interventions can create counterintuitive consequences and reinforce demand for informal connections*

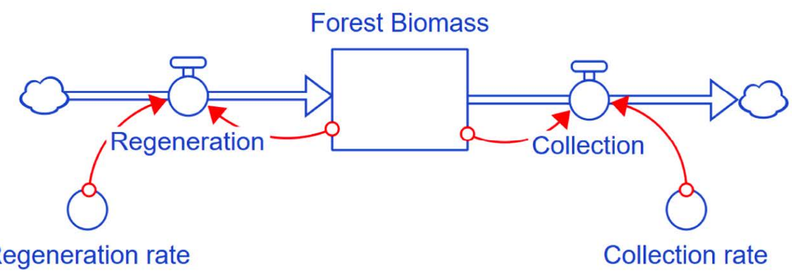


Quantitative system dynamics modelling with Stock and Flow Diagrams (SFDs)

While SFDs are usually the translation of a CLD into a quantified simulation model, it is also common to start a system study with an SFD if the focus is on quantification, simulation modelling, or user interfaces. SFDs contain all the elements and loops of a CLD, although they are not as visually accessible to a wide audience. It is therefore common for practitioners to tailor the modelling to the needs of the project or even create hybrid CLD/SFD visualisations.

SFDs represent the accumulation and flow of resources within a system. Turning a CLD into an SFD means the variables will become either a **stock** (ie a dynamic variable that accumulates or depletes over time, such as extractable resources, bioenergy crops, population, forest coverage, etc), a **flow** (ie the rate of change in or out of a stock, eg extraction rate, harvesting rate, birth rate, etc), or converters and external inputs which act as intermediaries in the calculation of flows (eg a percentage or a time delay aiding in the calculation of a regeneration rate).

***Figure 3:** The CLD featured in Figure 1 converted into an SFD. The quantity of available biomass becomes a "stock". Its value is dependent on the inflow of regeneration and the outflow of collection. The collection and regeneration rate help to quantify delays.*



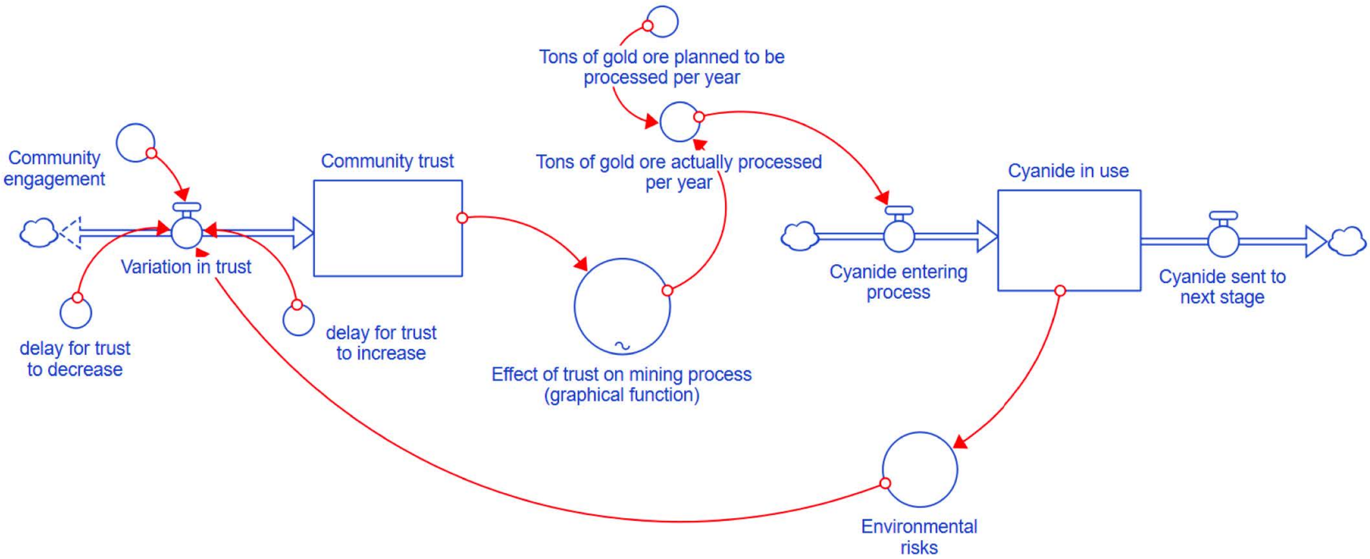
Non-linear relationships between system elements can be quantified using **graphical functions:** In the absence of reliable empirical data, modellers can rely on expert knowledge or stakeholder input to estimate these relationships, which commonly take the form of S-shaped curves, exponential growth or decay, and logarithmic patterns.

SFD Example: gold mining and trust

The mining industry must sustain its supply while facing significant environmental, social, and governance (ESG) risks, particularly those related to land use and environmental health and safety [11]. For instance, the majority of gold produced worldwide (90%) undergoes cyanide leaching, which can lead to declining levels of community and public trust. This raises an important question: is it possible to represent community trust, and how its evolution may influence the future of mining operations?

Trust can be conceptualised as a stock variable, because its value can accumulate or deplete over time (eg as a percentage or a level). The evolution of trust is non-linear: it might increase slowly through appropriate community engagement but may also deteriorate rapidly in response to failures in environmental health or safety management. A lack of trust can escalate into conflicts and incidents, impact communities, and lead to the shutdown of operations. By using a graphical function, it is possible to model the operational capacity of the company as a function of the trust it has earned [12]. This creates a dynamic multiplier effect, where levels of trust directly influence production outcomes.

***Figure 4:** A loop between trust, processing capacity, and environmental risks (simplified representation). More details in [12] and on https://exchange.iseesystems.com/public/smijkmrc/the-cyanide-socio-technical-learning-lab/index.html*



INTERACTIVE TOOLS FOR STAKEHOLDER ENGAGEMENT AND AWARENESS BUILDING

The development of publicly accessible dashboards and game-like interfaces is popular in SD. Web-based platforms allow modelling results to be shared and the broader context of a study to be communicated, such as the relationships between local communities and their livelihood, ecosystems, and land use. Examples can be seen on the isee Exchange™ platform hosted by isee systems [13].

Public SD interfaces have also been successfully used in policy, business, and educational settings to simulate global climate coordination efforts and explore the impact of cross-sector climate solutions on variables like energy prices, temperature, air quality, and sea level rise. Notable examples are the C-ROADS and EN-ROADS simulations developed by Climate Interactive and MIT [14].

Contributions and Added Value in LMICs

Since 2020, there has been an increase in studies using systems tools across a range of sectors in LMICs. The largest body of work is dedicated to the water–energy–food nexus, with other notable uses in energy, transport, and waste management. Many studies use system tools in conjunction with participatory approaches, with the aim of fostering inclusion and enabling communities to develop strong resilience mechanisms [15] [16].

More community representation, participation in political processes, and the reduction of marginalisation are recognised as important broader issues helping to avoid conflict and reduce inequality in LMICs [17]. Participatory approaches and qualitative SD tools are seen as particularly suitable for conceptual analyses in multi-stakeholder environments [18]. In general, the use of SD is considered a promising route of action to inform decision-making in contexts of uncertainty and risk [19], due to its capacity to engage with data scarcity through the use of graphical functions and expert input. Conventional data heavy modelling approaches which do not account for uncertain and intangible variables may run the risk of oversimplifying or missing important human and contextual issues that may vary across different LMIC settings and differ from high-income countries (HICs).

Systems approaches have been promoted for their ability to include a range of socio-technical, technological, economic, cultural, spatial, environmental, and political disciplines and integrate disparate sectors into a coherent modelling approach [20] [15]. There is also increasing interest in SD as a tool to enable the representation of agency and power interactions between actors (including unveiling conflicting goals that can create unintended consequences [21]), in addition to identifying the interdependencies created by non-linear relationships and the self-organising capacity of systems [15]. CLDs have also been used to facilitate communication between quantitative and qualitative analysts, offering a low-barrier entry point [22]. SD has also been used to inform planning and investment decisions towards enhancing food security, livelihoods development, socio-economic growth, and sustainable managements of natural resources [23]. Used in conjunction with political economy analyses, the use of CLDs was found to help identify leverage points for intervention in sustainable financing [24].

SYSTEMS CONCEPT: THE ICEBERG MODEL AND LEVERAGE POINTS

Unintended consequences or problems experienced by stakeholders are often the **visible symptoms** of a larger system structure that is shaped by patterns, structures, rules, and underlying paradigms – similar to the tip of an iceberg. Leverage points are strategic areas within a system where targeted interventions can influence system behaviour. The deeper the leverage point within the system, the greater its potential to transform the system as a whole. Donella Meadows defined 12 leverage points, ranging from "shallow" interventions, such as quotas and taxes, to deeper shifts in rules, goals, and mindsets (worldviews) [25]. This essential concept allows us to see beyond short-term actions which may lead to unintended consequences and instead fosters a deeper understanding of the root causes of societal issues. Doing so, it also encourages the adoption of more innovative modelling practices. In a CLD, leverage points are typically represented as policy interventions, and their level of leverage will determine their ability to influence the strength and direction of feedback loops throughout the system.

Most studies compare or simulate different policy interventions and contain clear policy recommendations. While it may be too soon to assess the policy impact of recent SD studies, it is clear that SD used in conjunction with participatory approaches can be effective in reconciling top-down with bottom-up perspectives and creating shared visions [26] [27]. As SD involves a shift to more systems thinking mindsets and awareness of systems behaviours, impacts may happen with delays or in indirect ways. For instance, the UK Government Office for Science, in collaboration with other stakeholders, published an introduction to systems thinking and toolkits for civil servants. In a government hosted blog, senior policymakers noted that systems thinking enabled them to spot systemic patterns they can leverage in policy design and implementation [28].

There have been a number of SD studies in the Climate Compatible Growth (CCG) programme's partner countries (Ghana, India, Kenya, Lao PDR, Vietnam, and Zambia). The SAFARI model is a fully quantified SD simulation model which examines the interdependencies between sectors competing for resources and energy in India [29]. A regionally disaggregated version (SAFARI-R) focuses on analysing the best interventions at national and regional levels to maintain sustainable food security [30]. Other models applicable to LMICs include LandYOUs [31] and FeliX [32], which offer adaptable, open source modules to study economy–energy–food dynamics.

There is clear interest in using systems mapping tools to study transition minerals globally. The transition to clean energies provides economic opportunities in both high- and low-income countries, and the stakes of securing critical minerals supply as well as avoiding financial ESG-related risks are high. As in other sectors, there are calls for approaches that consider economic, environmental, and social factors as well as public perception and regulation in the extraction and supply of critical minerals [33]. However, scholarship linking systems thinking to mining and minerals is nascent. There are scarce contributions in practice, especially those representing the complex land-use and human dynamics arising between communities and mining-related industries over the mine lifecycle. Most studies acknowledge the uncertain nature of the industry, intertwined human dynamics, and complex operation planning [34] [35].

Another topic of interest for systems approaches is Gender Equality and Social Inclusion (GESI), which is often incorporated within broader considerations of inclusion. Enhanced SD participatory approaches could also help overcome engagement challenges, improve inclusion, alleviate uncertainty, and integrate interdisciplinary and intersectoral perspectives [36]. These approaches still encounter barriers faced by more traditional modelling methods, such as high costs, time, expertise issues, inadequate involvement and transparency, model complexity, poor data availability, context sensitivity, or entrenched stakeholder divisions [37] [38] [26]. Despite these challenges, adopting a systems thinking lens to complement other modelling approaches presents exciting opportunities to enhance the integration of diverse factors and support more strategic and inclusive decision-making.

Opportunities and Next Steps

As demonstrated in this Knowledge Brief, SD offers significant opportunities in LMICs. Unlike traditional approaches that rely on static assumptions and idealised models, SD enables a more dynamic and realistic understanding of complex systems. It also allows for a broader and more nuanced assessment of challenges by considering wider consequences of change and progress, rather than limiting analysis to easily quantifiable elements. Placing systems thinking at the core of future project planning can help unlock more effective pathways for sustainable energy transitions. CCG has demonstrated its commitment to this approach through the EIMET project, titled ‘Exploring Innovative Modelling Approaches to Energy Transitions’ in LMICs. This makes it possible to incorporate influencing factors with greater realism and enhances the ability to perceive, interpret, and manage uncertainty while increasing stakeholder engagement and participation. Such capabilities are increasingly vital in development efforts aimed at supporting energy transitions while contributing to the delivery of the UN Sustainable Development Goals, ultimately strengthening societal resilience and reducing ESG risks in energy supply chains.

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