A System Complexity Approach to Swarm Electrification

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ABSTRACT

The study investigates a bottom-up concept for microgrids. Financial analysis is performed through a business model approach to test for viability when replacing a researched energy expenditure baseline in Bangladesh. A literature review compares the approach to current trends in microgrids. A case study of Bangladesh illustrates the potential for building on the existing infrastructure base of solar home systems. Opportunities are identified to improve access to reliable energy through a microgrid approach that aims at community-driven economic and infrastructure development by building on network effects generated through the inclusion of localized economies with strong producer-consumer linkages embedded within larger systems of trade and exchange. The analysed approach involves the linking together of individual stand-alone energy systems to form a microgrid that can eventually interconnect with present legacy infrastructure consisting of national or regional grids. The approach is likened to the concept of swarm intelligence, where each individual node brings independent input to create a conglomerate of value greater than the sum of its parts.

Keywords: Electricity Access, Bottom-up Microgrid, Microfinance, Bangladesh, Developing Country

INTRODUCTION

Across the Global South, infrastructure development, such as on the national electricity grid, scores high on the agenda in terms of national income invested.[1] At the same time, the UN Sustainable Energy for All (SE4A) target of universal energy access by 2030 is looming large[2], pointing to a greater part to decentralized options.[3] This leaves the question at hand what kind of infrastructure systems ought to be developed given past, present and future investments in micro and larger scale legacy infrastructure, ranging from small stand-alone solar home systems (SHS) to the national grid in order to reach the set target. Because without “the ability to avail energy that is adequate, available when needed, reliable, of good quality, affordable, legal, convenient, healthy & safe, for all required energy services across household, productive and community uses”[4] the affected people’s economic development is inhibited -or at least- delayed. The exact[5] number of people lacking of these electricity services

1 Dobbs R, Pohl H, Lin D et al. (2013) Infrastructure productivity: How to save $1trillion a year. McKinsey Global Institute.

2 Ki-moon B (2011) Sustainable Energy for All: A Vision Statement. United Nations Organization. New York.

3 OECD/ IEA (2011) Technology Roadmap Smart Grids. Paris: OECD/IEA.

4 Bhatia M and Angelou N (2014) Capturing the Multi-Dimensionality of Energy Access. LiveWire. The World Bank. Washington.

5 Groh S (2014) The role of energy in development processes - The Energy Poverty Penalty: Case study of Arequipa (Peru). Energy for Sustainable Development. 18. pp. 83–99.

so far remains unknown. What is known, however, is that despite increasing rhetoric on the need to change the situation of 1.3 billion lacking access to the national grid,[6] and another billion people with a severely intermittent supply number of electricity connection,[7] are outstripped by population growth in large parts of the Global South.[8] Discussions on this are usually centered around two key players of development: the government and the private sector. This approach fails, however, to take into account "the crucial third agent, in whose name development is carried out: people organized as communities and collectives, people seen not as 'beneficiaries' of the state or 'consumers' of private services but as drivers of their own destiny, empowered to self-provision basic needs and to govern from below".[9] Putting it into the language of complex systems, it is the "prosumer" who is the critical agent in the system, performing critical actions.[10] A prosumer in an energy system is "an economically motivated entity that: 1. Consumes, produces, and stores electricity, 2. Operates or owns a power grid small or large, and hence transports electricity, and 3. Optimizes the economic decisions regarding its energy utilization."[11] The complexity lies here in both the physical/technical and the social/economic dimension.[12] Weijnen et al., therefore, speak of infra-systems or infrastructural systems instead of infrastructures. They further argue that it is the socio-technical connection that crucially affects how the system performs. It is, therefore, precisely not dependent on initial system design or engineering from central entities who, once failing, can limit system performance, (e.g. mis-management or bad design affects livelihood aspects of households and businesses). User centered- models usually draw on the particularities of the complexity of energy systems rather than trying to avoid them, e.g. through using patterns of self-organization and emergence to grow the system by allowing for new business opportunities with a widening space of possibilities (e.g. prosumers). Only recently, the discussions on rural electrification have changed their dichotomous approach characterized by either centralized (e.g. national grid extension) or decentralized solutions (e.g. stand-alone SHS or isolated microgrids) towards the question of having access or the level of access.[13] This may be due to historic developments in the developed economies which made way for mental lock-ins. As a result, the economic calculus is based on the (non-) viability of grid extension, which is measured by the distance-based cost of extension. Villages too remote and with too low a load factor demand need to be electrified with a "second class" solution through a decentralized approach.[14] This paper joins the effort to distance itself from a binary category of energy access towards a multi-tier framework in order to be able to measure a continuum of improvement.[15] The service quality of electricity supply through the main grid varies substantially (e.g. in terms of black- & brown-outs, voltage fluctuation, among others) in different countries, regions of a country and even parts of the same city. The quality of decentralized energy systems varies even more in terms of possible loads to connect, time and duration of usage. Thus, a mere measurement in overall supply (Wh) per household counteracts a strive for more energy efficient appliances that run with those systems, thus neglecting the importance of the load attached (W). These multiple access solutions, partly designed as transitional solutions or even running in parallel, need to be assessed reflecting these differences in service supply. Therefore, reference is taken here to the multi-tier approach to measuring energy access, distinguishing five tiers based on six attributes of electricity supply. Nonetheless, the technology options presently discussed under the tier framework are all "engineered" in a certain size, with certain assumptions, for certain purposes. Space to act for the end-user remains very limited. The future notion should thus

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6 IEA (2012) World Energy Outlook 2012. Paris: OECD/IEA.

7 AGECC (2010) Energy for a Sustainable Future. Secretary-General's Advisory Group on Energy and Climate. Summary Report and Recommendations. New York.

8 Pachauri S, Ruijven BJ, Nagai Y, Riahi K, van Vuuren BJ, Brew-Hammond A and Nakicenovic N (2013) Pathways to achieve universal household access to modern energy by 2030. Environ. Res. Lett. 8. pp. 7ff.

9 Kothari A and Shrivastava A (2013) Economists on the Wrong Foot. Economic and Political Weekly. Vol. - XLVIII No. 33, August 17, 2013.

10 Ritzer G, Dean P, Jurgenson N (2012) The Coming of Age of the Prosumer. American Behavioral Scientist. 56(4). pp.379-398.

11 Grijalva S and Tariq MU (2011) Prosumer-Based Smart Grid Architecture Enables a Flat, Sustainable Electricity Industry. IEEE.

12 Weijnen MPC, Herder PM and Bouwmans I (2008) Designing complex systems: A contradiction in terms. In Eekhout, M., R. Visser and T. Tomiyama, Delft Science in Design. A Congress on Interdisciplinary Design.Vol. 3. pp. 235-254.

13 Tenenbaum B, Greacen C, Siyambalapitiya T et al. (2014) From the Bottom Up - How Small Power Producers and Microgrids Can Deliver Electrification and Renewable Energy in Africa. The World Bank. Washington.

14 Mandelli S and Mereu R (2013) Distributed Generation for Access to Electricity: "Off-Main-Grid" Systems from Home-Based to Microgrid. Book section. In: Renewable Energy for Unleashing Sustainable Development. Springer Press. pp. 75-97.

15 Energy Sector Management Assistance Program (2014) A New Multi-tier Approach to Measuring Energy Access. Available under http://www.esmap.org/sites/esmap.org/files/DocumentLibrary/Multi-

tier%20BBL_Feb19_Final_no%20annex.pdf. Last accessed: August 21, 2014.

not be centralized versus decentralized (nor access versus no-access) systems designed to cope with complexity but on robust, adaptable, fast changing (self-organizing) infra-systems that use complexity for their advantage. The latter are characterized by the co-evolution of supply capacity and respective (economically feasible) demand that fits the overall system size. These systems achieve their robustness through usage of information and communication technology (ICT) -convergence- in order to communicate power, information and monetary flows that keep the physical system stable (e.g. by intervening when the system moves far from equilibrium (demand >> supply or demand << supply), constraining actions such as using devices with too high demand) while signaling actors when new spaces of opportunities open up (e.g. by integrating new storage or generation capacity that creates income for the actors; or use cheap and abundant electricity for productive purposes, respectively).[16]

The authors assume that in certain scenarios a paradigm shift away from exogenously engineered approach to user-centric emergence schemes may lead to a better system performance. Furthermore, the authors hypothesize that such a paradigm shift could improve on existing decentralized methods for rural energy, including stand-alone one-off SHS and baseline energy fuels such as kerosene. This research seeks to further look into this hypothesis through the analysis of a newly developed bottom-up concept, referred to as swarm electrification (SE), a sharing-based energy infra-system, based on decentralization and resource efficiency.[17] SE is based on nodes in a swarm intelligence network where information and electricity flows are shared among neighbors “to achieve a compounding network effect, in that they are linked together to form a microgrid – to achieve a networked grid effect.”[18] The concept follows the principle of a bottom-up initiative, often referred to grassroots innovations, in the sense of that it is a decentralized track which is generally carried out through non-governmental entities such as cooperatives, community user groups, or private entrepreneurs and households. Smith et al describe grassroots innovations as “movements seek innovation processes that are socially inclusive towards local communities in terms of the knowledge, processes and outcomes involved.”[19] The SE concept further envisions a readiness toward the actors and infrastructure of the centralized track, being the utilities and the national electricity grid. The objective of this paper is therefore to investigate the feasibility of an approach where the people themselves start building upon their present resources in order to form a balancing network and prepare themselves for an eventual grid connection. Given the unpredictability of system emergence, the underlying research question raised here is whether such a grid can be built from the bottom-up avoiding path dependencies and leading to more resilient and ultimately sustainable infra-systems. Sustainability is here not understood as a condition of stasis but “a process of continuous adaptation, of perpetually addressing new or on-going problems and securing the resources to do so.”[20]

16 Weijnen MPC and Bouwmans I (2006) Innovation in networked infrastructures: coping with complexity. Int. Journal of Critical Infrastructures. Vol 2(2). pp. 121-132.

17 Groh S, Philipp D, Edlefsen B, Kirchhoff H. (2014a) Swarm Electrification - suggesting a paradigm shift through building up microgrids bottom-up. Proc. of the Int. Conf. Innovating Energy Access for Remote Areas: Discovering untapped resources. Microenergy Systems and Berkeley Rural Energy Group. Berkeley, USA. 2014; ISBN: 978-3-7983-2694-1.

18 Groh S, Philipp D, Edlefsen B, Kirchhoff H. (2014) Swarm Electrification - suggesting a paradigm shift through building up microgrids bottom-up. Proc. of the Int. Conf. Innovating Energy Access for Remote Areas: Discovering untapped resources. Microenergy Systems and Berkeley Rural Energy Group. Berkeley, USA. 2014; ISBN: 978-3-7983-2694-1.

19 Smith A, Fressoli M, Hernán T (2014) Grassroots innovation movements: challenges and contributions. Journal of Cleaner Production. 63. pp. 114-124.

20 Tainter JA (2011) Energy, complexity, and sustainability: A historical perspective. Environmental Innovation and Societal Transitions. 1.pp. 89–95.

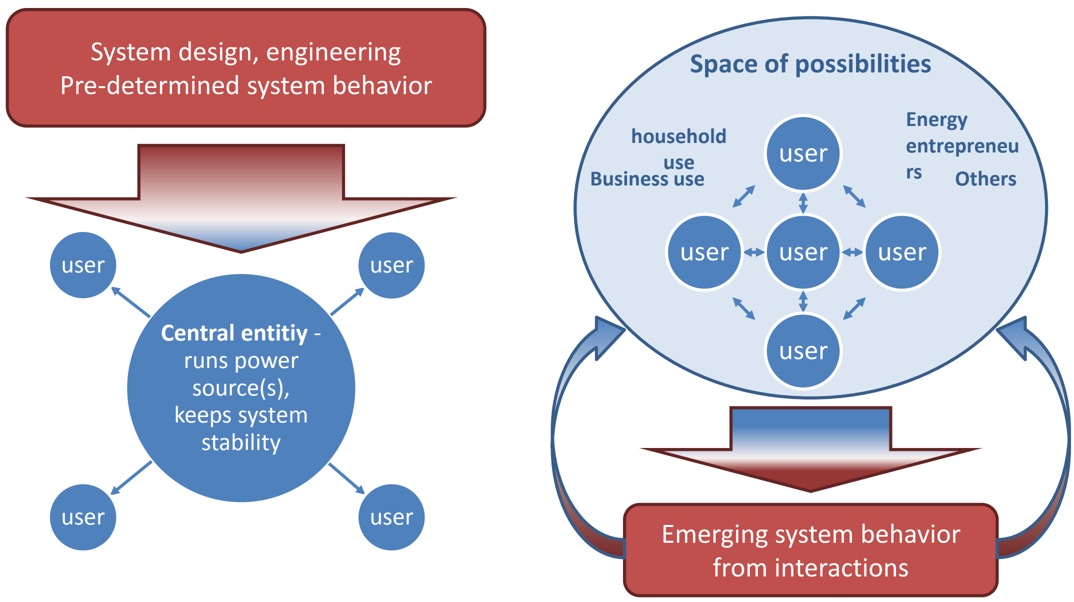

Figure 1: The (mis-) understanding of electircity infra-systems vs. the bottom-up swarm approach

From the perspective of complex system theory, the authors analyze a bottom-up concept drawn from an approach that follows the basic principles of swarm intelligence in distributed information and communications technologies networks.[21] In the swarm electrification scheme, each individual node brings independent input to create a conglomerate of value even greater than the sum of its parts. In the way that each node in a swarm intelligence network shares information with its neighbors to achieve a compounding effect, individual stand-alone household energy systems could share electrical power. Hence, each node/agent acts independently while her action influences other agents and her own future way of acting (connected and interdependent entities in a dynamic environment), thereby opening possibilities for non-intended actions (non-predictable emergence) benefitting the system (or community, but finally feeds back to electricity system as well). Finally, a stable (and self-stabilizing) system component is attractive for the larger system to connect to, in order to create more overall stability and robustness. In our understanding, a bottom-up approach is mainly characterized through its user-centricity. Figure 1 shows the main difference to a centralized-planned approach.

Whereas the latter is designed for a specific purpose and thus rigid and dependent on a single central entity to manage it, the bottom-up system ought to be

- non-pre-engineered, meaning it can adapt and re-configure (through built-in ICT solutions), leading to path-independency and the avoidance of legacy infrastructure problems,
- user-centered, meaning it does not depend on one single entity or agent to run the system, thus leading to higher robustness (comparable to the built-in-robustness of electricity systems under the so called “n-1 criterion”, meaning the user and clusters of users and their interaction will lead to a site-specific emergence of overall system behavior which in turn opens up new possibilities for the users both as consumers and producers of energy while constraining other actions.

21 Groh S, Philipp D, Edlefsen B, Kirchhoff H. (2014a) Swarm Electrification - suggesting a paradigm shift through building up microgrids bottom-up. Proc. of the Int. Conf. Innovating Energy Access for Remote Areas: Discovering untapped resources. Microenergy Systems and Berkeley Rural Energy Group. Berkeley, USA. 2014; ISBN: 978-3-7983-2694-1.

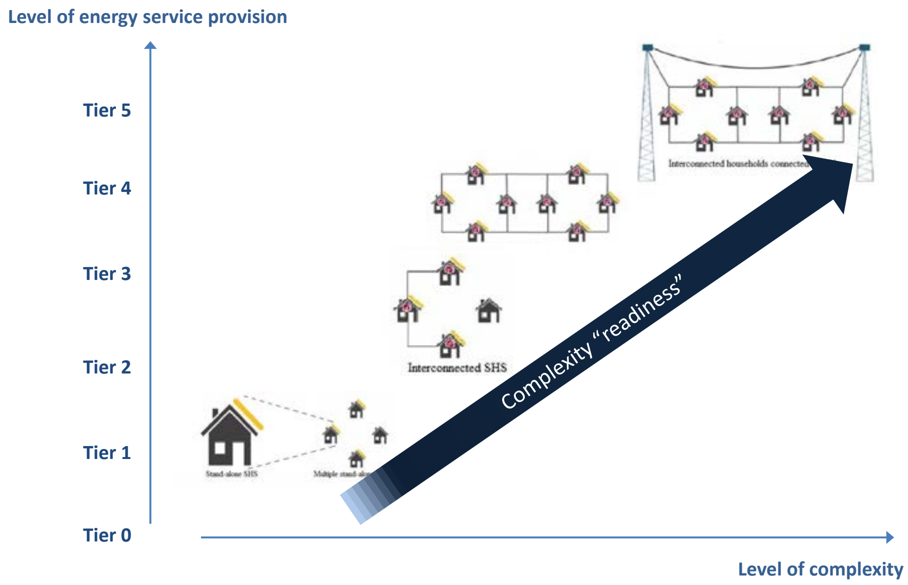

Figure 2: Swarm electrification steps in the context of tier based service provisions and added complexity

DRAWING FROM THE BANGLADESH EXPERIENCE: IMPLICATIONS FOR A COMPLEXITY-EMBRACING APPROACH

Applying the concept of SE and interlinking these clustered SHS to form a microgrid, end-users could act as "prosumers", as agents of a newly formed local energy system. These agents are then empowered to consume electricity from the microgrid as well as feed electricity into the microgrid and thus generate direct income. The interconnection has the potential to create synergy effects. The emergence of macro-patterns through the connection of people and technology triggers the conversion of the SHS from a mere energy source to a business-enabling vehicle. But at the same time the process increases interdependence which may lead to catastrophe. These aspects need to be taken into consideration at the device layer where smart devices can provide mechanisms for local control and beyond that are dynamic.[22] This control unit can be referred to as the system communication controller, robustness controller, energy flow manager, or monetary flow manager. The key aspect here is that it can be easily (re-)programed in order to account for unpredictable behavior. With recent advances in smart grid technologies as a consequence of the convergence of energy and ICT, such a bottom-up interconnected electrification approach can become feasible.[23] Unlike traditional microgrid approaches, there is a dynamic participatory inclusion of community members based on their existing equipment assets. A new system is built based on a myriad of existing sub-systems. As each agent can also act independently, varying degrees of the quality/ health of the systems do not interfere. Utilizing systems that are already existent in a particular household or business helps to minimize challenges associated with generation and storage sizing basically taking it from a complicated task to a complex system, while allowing the agents in the infra-system to share power and thereby balance out mismatches over time. By forming a village-scale microgrid connection through the network of electricity-sharing homes, the agents make use of their differentiated energy generation, storage capacities and consumption patterns to allow for a more efficient and consistent electricity service for all involved: both for SHS-equipped as well as non-equipped households and businesses. This again adds complexity but also a significant amount of benefits in terms of energy inclusion. Figure 2 illustrates the step-wise approach of SE in the context of tier based service provisions and added complexity. Step one shows individual households equipped with DC SHS as well as houses with neither solar nor grid electricity supply. Step 2 shows the interconnection of households with SHS, whereas in Step 3 the remaining houses are included in the growing DC microgrid. In step 4 different clusters can be interconnected. As a final step, the microgrid can be connected to a national or regional grid with minimal points of AC/DC conversion interfaces. The resulting

22 Grijalva S and Tariq MU (2011) Prosumer-Based Smart Grid Architecture Enables a Flat, Sustainable Electricity Industry. IEEE.

23 OECD/ IEA (2011) Technology Roadmap Smart Grids. Paris: OECD/IEA.

network is a DC grid that can facilitate trade and increase usage flexibility and reliability beyond the status quo of one-off systems. The advantages such as better system performance due to better battery charging cycles, more flexible usage of electricity, better system integration and opportunities for increased income generation through acquisition of bigger panel (and battery) sizes are reflected in the evolutionary development across the different tier levels. In terms of the ability to cope with the characteristics of complexity as described above, there is an important pattern to observe. While the increase in complexity per se is rising progressively, the demand for the ability to deal with socio-technical system complexity is more dualistic. While single, stand-alone systems do not need to have it, connected systems with multiple agents need them. Thus, the ex-ante incorporation of complexity-handling ICT not only enables systems with swarm controllers to connect to the grid but actually attracts the grid to connect to them once they reach critical size. Village-level micro-grids that were built from the bottom up can generally be able to serve high-power appliances for productive use. However, they face the problem of legacy infrastructure (electrical wiring) due to the assumable concentration on low-invest equipment in the first development stages of the system. As such, unlike traditional microgrids, the swarm model might need to tackle the challenge of limitations that occur when the technical system remains dependent on the existing SHS cabling and voltage levels, thereby retaining the instantaneous power draw limits of the SHS even if the overall energy availability and system performance increases. This represents the downside of the usage of existing resources and legacy infrastructure, even though in this case the infrastructure investment is considerably lower. The graph above reflects this issue where the jump from tier 1 to tier 2 occurs with only little increase in complexity. It must be noted, however, that the transition from tier 1 to tier 2 is critical as the technology undergoes changes from a single-device artefact (single lamp) to a more complicated technical system (SHS). This system interacts with the user layer, but the number of agents per system involved remains minimal. The first step of interconnection and consequently the upgrade to tier 3 level, however, results in a stronger increase in complexity due to the network system and interdependencies. The transition from tier 4 to 5 then has even more increase complexity when bottom-up and top-down infra-system are integrated into each other, leading to an overlay of networks with multi-role agents. Applying the 4A criteria to the concept, a central public value comes into play set out by the GoB in its Vision 2021: universal electricity access. In order to be able to assess the swarm concept against this goal, feedback loops are analyzed through graphical illustration. It is an attempt to show the logic and dynamic behind the 4As scheme. Figure 3 discusses the impact of a combined energy and financial inclusion measure, which seem to be mutually related as debated in Khandker et al. (2012), as well as in Groh and Taylor (2013), on an existing vicious cycle of a low income combined with high energy cost and limited usage capabilities from poor energy services, in short an "energy poverty penalty."[24] Tier 1 and 2 provision of electricity services cover basic needs but also give the people a taste for electricity resulting in higher electricity demand patterns as shown in Figure 4 below and observed by various authors. A case study of SHS in Zambia showed that energy demand in the household increased with time, leading to over-usage of the systems.[25] For mini-grids the same applies: a study in India demonstrated that "people gradually started to look for more electricity."[26] Another study from China showed a significant drop in service time from 12 to 3 hours per day for due to over-usage.[27]

24 Groh S (2014) The role of energy in development processes - The Energy Poverty Penalty: Case study of Arequipa (Peru). Energy for Sustainable Development. 18. pp. 83–99.

25 Gustavsson M (2007) With Time Comes Increased loads—An Analysis of Solar Home System Use in Lundazi, Zambia. Renewable Energy. 32(5). pp. 796 – 813.

26 Ulsrud K, Winther T, Palit D, Rohracher H and Sandgren J (2011) The Solar Transitions Research on Solar Mini-Grids in India: Learning from Local Cases of Innovative Socio-Technical Systems. Energy for Sustainable Development. 15(3). pp. 293 – 303.

27 Shyu CW (2013) End-users' experiences with electricity supply from stand-alone mini-grid solar PV power stations in rural areas of western China. Energy for Sustainable Development. 17(4). pp. 391-400.

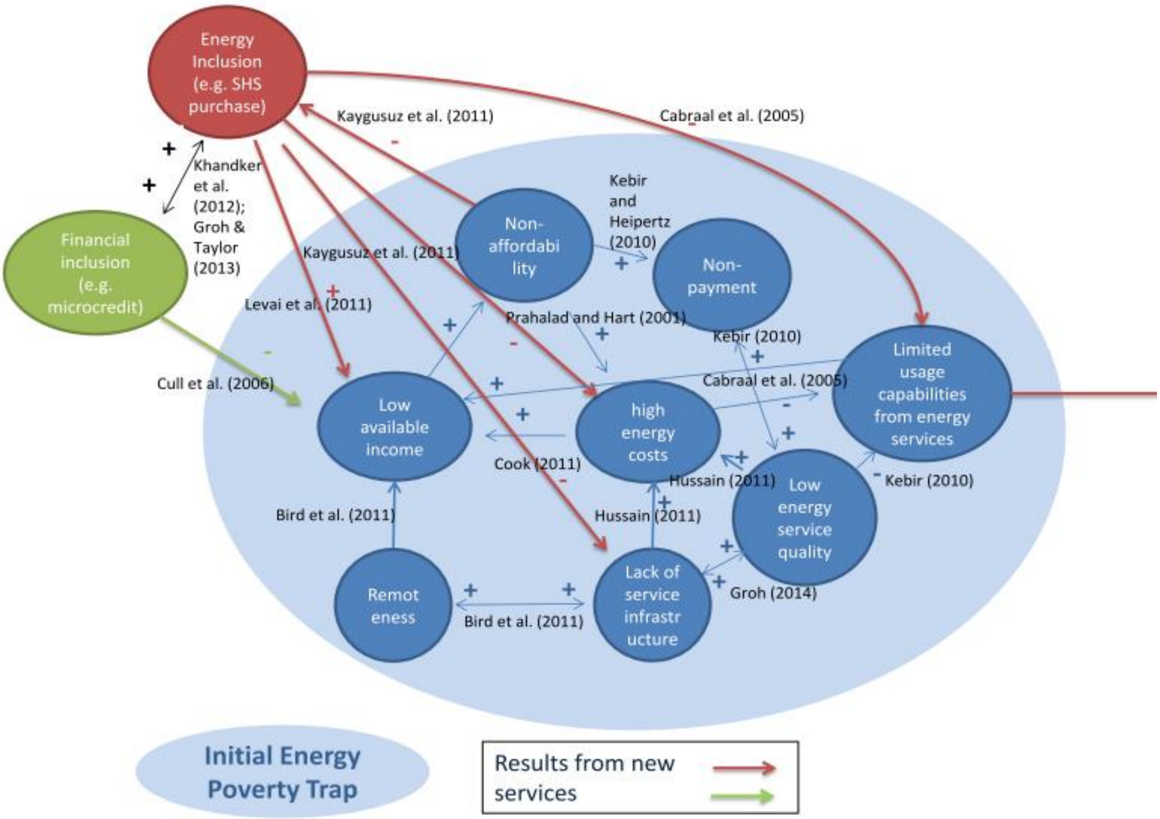

Figure 3: Household and microbusiness based feedback loops

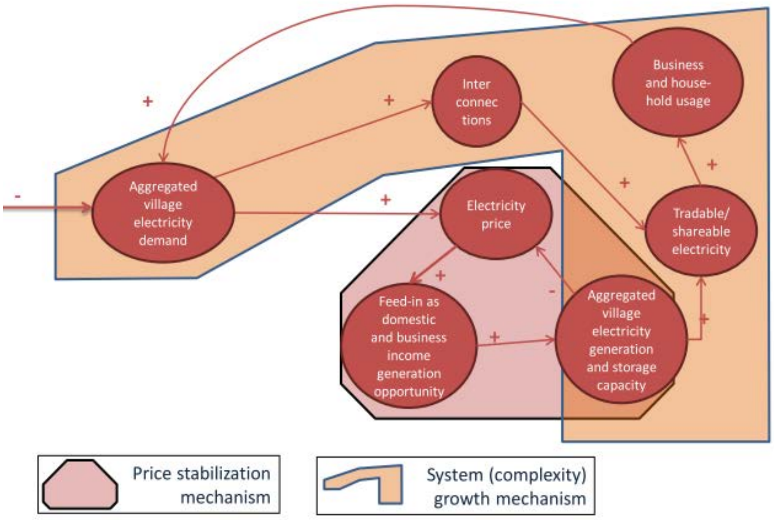

Figure 4: System feedbacks on village level

Figure 4 distinguishes between a system complexity growth mechanism which has been earlier described along the tier framework in Figure 2 and a price stabilization mechanism. In the latter one it is important to note that depending on the incentives set though dynamic pricing there are two possible dynamics: First, it can stimulate higher demand which can be realized system internally but also through extension to net consumers which translates into additional electrification. Second, it can trigger entrepreneurial behavior aiming for surplus generation capacity that can be traded.

CONCLUSION

Although, the concept has a built-in opportunity for scalability, the issue of replication potential for other perhaps less densely populated areas and countries remains to be seen. However, generally speaking, the concept seems to be applicable in all off-grid areas where there is a certain density of social and economic activity. As SE so far remains a theoretical model, as a next step dynamic growth models testing the assumptions need to be computed as well as field tests conducted with a close monitoring. Looking at energy access efforts through the lens of system complexity can reveal strengths and weaknesses of approaches ex-ante and ex-post. In the light of many unsuccessful approaches in the past, there is a strong need to avoid similar pitfalls in the future. The authors hope that this is rather a starting point in a new discussion than a final statement. Based on our analysis, we argue that future infra-systems must be treated complex rather than complicated. The need for the incorporation of complexity with all its characteristics might thus be larger than the need for precise system layout from the beginning. Systems need, therefore, to be built bottom up avoiding “unhelpful forms of top-down intervention” [Lewis, 2011, p. 196]. This means that the electricity infra-system in the Global South has the chance use the convergence of ICT and energy, coupled with innovations in both areas, and leapfrog technology by avoiding legacy infrastructures. The tools and concepts to design adaptable, robust, decentralized, democratic and socially just electricity systems are in place.