A Sustainability Framework for Off-Grid Electricity Access Projects in Developing Countries

PhD Thesis

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Abstract

For many of the nearly 771 million people currently without electricity access, distributed generation, rather than a connection to a large centralised grid, will be the norm. Distributed energy such as stand-alone solar photovoltaic (PV) systems, mini-grids and pico-lantern products are viable options used to complement or supersede grid-based solutions since they can be deployed in smaller batches and avoid the need for the more costly transmission and distribution equipment.

Success of an off-grid project, or programme composed of multiple projects, requires that it is sustainable; it must survive long enough to achieve its design objectives and promise of progress for its users. For society at large, failure of sustainability of projects wastes the considerable investments made towards achieving universal energy access – a direct outcome of the United Nations Sustainable Development Goal Seven. For households and communities, failure undercuts potential socio-economic impacts and limits the ability for people to live with basic dignities of education, health, and economic opportunity – all of which require electricity access.

The record of sustainability of off-grid programmes are mixed, with some achieving degrees of serviceability and others failing altogether. The literature describes a complex web of interrelated sustainability factors at play in off-grid electricity access projects. They are commonly organised across economic, technical, social, organizational, and external classifications. There is currently no general template or formula that, if applied, produces a consistently sustainable project. An analysis of the literature herein around project sustainability has revealed inconsistencies in the scope, definition, comprehensiveness of evaluation methods and toolkits to capture sustainability. Literature at the project-level literature is mostly composed of anecdotal evidence.

A review in the thesis of specific sustainability issues affecting projects confirms ongoing challenges and refreshes the current understanding of sustainability. Three new case studies are presented in the thesis which reveal new operational sustainability issues and provide insights into the limitations that project design has on operations, all of which are previously undocumented in the literature. The analysis of the literature finds a knowledge gap which follows from a lack of systematic learning. This thesis addresses this gap by proposing a sustainability framework to systematically understand, model, and evaluate sustainability factors to better prepare future projects for success.

The framework links together the design, operations, and evaluation of an off-grid project's life-cycle using project-centric indicators. A learning dimension is overlaid on the framework to set the groundwork for retaining comparable learning generated from one project to the next. Each stage is driven by the findings from a novel model developed for a generic off-grid project which extends the functionality of a techno-economic optimisation for sustainability analysis. A virtual operator makes operational decisions throughout a 20-year simulation of the project's operations where time-series data and indicators can be produced in order to evaluate performance. Several new social and organisational aspects are introduced and have an impact during the operational stage: proportion of energy allotted for various end-uses, investment in training, price setting, price elasticity, and socially-driven demand responses. The model more accurately reflects the context of off-grid projects and captures dynamics that could be used in the design stage to improve sustainability prospects. Simulation results over 23 distinct scenarios demonstrate the use of indicators during the operational stage and validate the importance of operational sustainability issues. An extensive evaluation of the generic project could be repeated on others in order to produce more robust evidence for future toolkits. These contributions will be directly useful for a number of audiences: project designers, project implementers, policy makers, and for the project beneficiaries themselves.

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Contents

List of Figures

List of Tables

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Chapter 1

Introduction

1.1 Motivation

1.1.1 Personal Motivation

In 2014, I had the opportunity to visit several off-grid projects involving solar photovoltaic systems at schools and health centres in the rural District of Chikwawa in Southern Malawi. The projects were organised to be run by the community by an energy committee setup that ran the local operations. The purpose of the visit was to document the projects' sustainability and impact on the lives of the beneficiaries. During the visit I interviewed community members who benefited from the project. This was both humbling and thought-provoking as I spoke to the school headmaster, energy committee, health assistant, parent teacher association liaison, student representative and several senior teachers.

The community was clearly economically poor: many pupils had well worn clothes, the roads were unpaved, and housing consisted mostly of structures with dried mud-walls and straw roofs. Yet the project had brought change to the community. The villagers explained how access to electricity at the school had enabled the young pupils to study in the evening and invigorated the staff by providing the basic necessity of light. The pupils' opportunity to learn, and go on to better their livelihoods had been advanced. As the community answered our questions, their pride of ownership and sense of progress in the community was palpable. At a personal and professional level, as I have later been involved in the development of similar such projects, enabling this development has been a source of immense satisfaction and accomplishment.

Despite my initial appreciation of the apparent outcome of the project, closer inspection of the state of the project revealed several concerns. I asked about the project ownership, finances, technical system operation, and community support. Capturing this evidence was basis of the sustainability evaluation. It was recounted that the project had functioned for a time but it had stopped working for over a year at the time of the interviews. The reason for this seemed to be simple, a fuse on the charge controller had failed, which prevented it from charging the batteries or supplying the system load. The solution was obvious: use the savings the project had accumulated to replace the fuse.

Further investigation revealed that the project had not saved any funds to replace faulty equipment. The revenue generating activity (charging mobile phones) had ceased when it was ascertained that a single beneficiary had taken the funds generated up to that point, adversely impacting the economic sustainability of the project. Inspection of the wiring found that someone had bypassed the charge controller and connected the panels directly to the battery and battery directly to the Direct-Current (DC) loads, undermining the technical sustainability. It was likely the batteries were permanently damaged, most likely by deep discharging and high rates of charging/discharging cycling. Furthermore, it turned out that the energy committee meetings, which was meant to be managing entity responsible for the project, was poorly attended and rarely met, mainly to reconfirm that nothing had been done (a sign of poor organisational sustainability). With the system not bringing in any funds or providing electricity, eventually someone had stolen some of the panels, indicating a breakdown in social support. Neither the thief nor panels were found. The Energy Committee pointed out that there was no qualified technician in the village or surrounding area who could fix the system. Moreover, they said they were hesitant to reach out to anyone since both they and the Group Village Chief, the traditional leader, had said that they did not have authority to "do anything" with the project (a weakness in the design of the project which did not manage to create sufficient ownership). Instead, it was understood that the authority was in the hands of both the grantor, who supplied the original funding, and the local installer, a technician from the closest town centre. The committee members were worried that intervening in the project would upset this relationship with them and the grantor. The committee had at first been able to use the funds generated from the project to purchase uniforms for orphans in the community as well as some classroom supplies – but even this was no longer possible. Thus the current state reduced the overall developmental impact of the project.

How sustainable was this project? What appeared at a superficial level to be a simple problem and solution unravelled into a complex web of problems. It was intuitively clear that these issues each combine to undermine the sustainability of the project. Understanding the causal relationships associated with their occurrence would be key to determining an accurate estimation of the level of project's sustainability. With this question in mind, the team of researchers and support staff for the project, the 'experts', then discussed the conclusions which could be drawn.

At first the argument was made that the quality of the equipment, which had broken down, was the main issue. Higher quality, more robust equipment which could handle the rugged installation was required. It was pointed out that user behaviour may have played a part. Why did the fuse blow, was it because the users tried to connect too large a load? Or perhaps it was the original design itself which was inherently under-sized?

Alternatively, one of experts argued that the weakness was the economic model. The income generation scheme needed to bring in more revenues that could also be transparently managed. These funds could have been used to easily replace the fuse and other equipment which had broken. Given enough time, all equipment will break, so clearly went the argument, it was the economic system at the root of the problems.

Yet another expert argued that project ownership and low skills was the root of the problems. Since one person had managed to the subvert the funds for personal use, the committee was not or could not act as owners in the best interest of the project. Why were they not capable of fixing the technical fault or finding someone? Several observations were pertinent. First, they lacked technical skills to maintain the system. Second, they lacked the authority to remove the individual taking advantage of the project and re-establish its purpose. Third, they acted as passive users rather than owners; why did they not initiate any potential solutions to the problems that they observed? Finally, it also became clear that the energy committee was filled with many members of the education committee. Their preference was to achieve near-term educational outcomes by using the project as a source of educational funding although this was at odds with maintaining a savings account to support the energy project.

Finally, another explanation came in the form of how the project was embedded within the community. The theft of the panels showed that the legal framework was not sufficient to protect the relatively valuable equipment along with their promise of transformational change. The village social system, in which community coherence and support systems often are the defining feature of village life, was insufficient to protect this asset. Furthermore, the agreement between Committee and Chief that the project was owned by external groups suggested that the project was more like a foreign object inserted into the heart of the community rather than community-owned development asset. Thus, the project needs to be re-embedded into the community such that a sense of wider ownership is built up along with a clear management role to protect it.

At the end of the evaluation, it was clear that making a judgment on the level of sustainability and attributing this to any one reason was a complicated matter. While intuitively it was apparent that many factors could be identified as a contributing factor to the projects sustainability and success, the extent of each factor's contribution was not obvious. It was important to link to problems to results over the sequence of events of that occurred over the project's timeline. The issues being faced at any one time were the result of many decisions that had been made in the past. Furthermore, the process of evaluation and potential conclusions that were made depended on the evaluators and the weighting given to specific factors. Unsurprisingly this seemed to follow the disciplines of the specific person: the engineers concluded that the technical issues were at fault whereas the social scientists held that the project inception plan and organisational aspects were ultimately the problem.

1.1.2 Sustainability of Off-grid Projects, the Global Perspective

The narrative of the project shares similar challenges to many other projects installed throughout the developing world today. The development community, engineers, and local communities are aware that the sustainability of these projects is uncertain and energy access practitioners have faced a steep learning curve when deploying off-grid projects. Today, the efforts to achieve universal access to electricity are unprecedented, but even while gains are made, many projects end in partial or total failure.

The learning process is ongoing but inconsistent. There is no one template to ensure sustainability because projects are deployed in a complex environment that is not fully understood, or sufficiently modelled, by project designers. Sustainability evaluations, undertaken no more than two years after commissioning are the defacto mode of learning. The short time period between commissioning and evaluation as well as dependence on a single point in time to make this evaluation reduce the amount and quality of what is learned. Unfortunately, to date there is no widely used methodology for sustainability evaluations. Conclusions tend to be subjective as both the language and emphasis varies from one evaluator to the next. Only a fraction of projects deploy monitoring and evaluation metrics and these are individually customised to the project by the designers. When used, these metrics are usually for the purpose of recording impact performance, not sustainability. This shortage of data and method leads to ad hoc evaluation approaches inexorably ending with an expert opinion. The cycle repeats as the next practitioner reads the documentation on how to make their project sustainable and starts off with an incomplete picture. True learning on sustainability is thus bottled up in the experiences of a handful of prominent practitioners who each have a unique explanation and understanding of what makes their project sustainable.

As practitioners, academics, governments, and communities move towards the overall goal of providing electricity access for the 1 billion people today currently living without access, providing sustainable solutions is an imperative to avoid lost investment — switching the lights on is one aspect of the energy access problem; keeping them on is arguably even more challenging. The ability of projects to survive and thrive is a key premise to attaining the global impacts that are targeted, but this premise has not been proven. Most importantly, the difference made to the lives impacted cannot be understated; failure to provide sustainable electricity access will prevent development of the poorest communities in accessing opportunities to live healthy and productive lives. This thesis argues that the rhetoric of universal access can be achieved only by realising that a systematic and consistent process of learning is needed to identify and prove sustainable models for energy projects.

Project design methods that are weighted towards ensuring a sound techno-economic system optimisation have not proven sufficient to ensure project sustainability as a whole. Social, organisational, and external factors to a project are often too important for the project's sustainability to overlook. A concerted effort is needed to promote a systematic learning, where the impact of innovations can be evaluated holistically and compared to other projects. This will improve the ability to tease out effective innovations that have import on sustainability from conjecture, and ensure that they have the evidence base to influence future project design.

1.1.3 Research Objectives and Novelty

This thesis argues that the off-grid practitioner network and development community needs a consistent approach to the documentation of learning around the sustainability of off-grid projects in developing countries. It is hoped that the contributions will influence **project design methods** – notably by using improved modelling methods that are more holistic and representative of actual project experiences. In addition this work highlights the considerations of **project sustainability during operations**, shifting the focus of evaluations towards sustainability and capturing of indicators which can be used periodically to reliably assess project sustainability. In particular, it addresses the role that **operator and customer decision-making** plays to promote or detract from sustainability. These organisational and social dynamics that occur though a project's life-cycle demonstrate the feasibility of extending the techno-economic optimisation modelling that is common to off-grid projects. This research advances the **indicator framework methods** for sustainability evaluations to adhere to a new criteria relevant to project-level sustainability. Finally, a **conceptual framework for**

project sustainability is proposed to produce systematic learning that iteratively builds the knowledge base on factors for failure and success.

A summary of the contributions of this thesis are listed in Table 1.1 below, along with a statement explaining their novelty. This is provided here for the convenience of the reader though it should be noted that further explanation of these contributions are provided in Section 1.4.

Table 1.1: Contributions and Novelty

No.	Contributions	Novelty
1.	{a} Development of a new definition of 'sustainability' of off-grid electrification projects and {b} innovations of sustainability indicator selection criteria	Origins of existing definitions are investigated and synthesised with respect to relevance to off-grid electricity projects in developing countries. The critical analysis finds the existing usage of the term unsuited for this context. As indicators have been used to operationalising this definition, a gap analysis refines useful aspects and new innovations are added (project sustainability, comprehensive, comparable, robust)
2.	Critical review of defacto standard methods: {a} indicator frameworks, {b} sustainability toolkits and {c} techno-economic optimisations – for sustainability design and evaluation.	Gap analysis on each method revealed inconsistencies (i.e. scope, definition, comprehensiveness) that ultimately limit the relevance to context. Inconsistencies are apparent within each method and equally between methods. This develops project-centric definition of the term 'sustainability' which is applied to (3). This critique is accompanied with recommendations that lay the foundation for the modelling and discussion in (4) and (5).
3.	New understanding of sustainability issues including quantitative (insights into concentration of issues per factor, and occurrence of specific issues), and qualitative (operational issues and relationship between design and operation).	Review covers 21 countries over a 18 year time-span. This updates to prior comparisons is provides a fresh review of the current state of sustainability. This considers the revised definition as per (1). The meta-analysis of concentration of issues is new to this context. Case studies reveal new operational sustainability issues and provide insights to the limitations that project design set on operations all of which are previously undocumented in the literature. Additionally, one case study shows a (novel) relation between provision of free social goods and demand for electricity services from the project which is modelled later in (5).
4.	Development of a holistic sustainability project model and simulation.	A novel model is developed which extends the defacto standard approach of techno-economic modelling to include social and organisational dynamics throughout the project life-cycle. Specific novel features include an operator and customer decision-making framework, incorporation of a wider range of sustainability categories, and application of the model to the operational phase of a project. The model and subsequent insights revealed from the simulations are each related novel contributions. The dynamic context suggests different strategies are viable at different project stages (such as pursuing a primarily pricing or reliability strategy).
5.	Development of a systematic sustainability conceptual framework for off-grid project learning	The framework links design, operations, evaluation stages of a project life-cycle with project-centric indicators and addresses gaps found in (2). Existing frameworks do not comprehensively consider all stages. Proposes an overlay of learning, through indicators, as it relates to each stage. Results from (4) are shown to have value to a project in each phase and argue for continuous improvement as projects complete the cycle.

1.2 The Gap in Access to Electricity

Access to electricity in developing communities through off-grid projects has become a prevalent trend and is likely to be a major approach taken over the next several decades. Although this offers new hope for communities to bypass the traditional but painstakingly slow means to electrification, via central grid expansion, the relatively low level of sustainability of off-grid projects is of critical importance. This chapter aims to provide a background to the first point by covering, first, an overview of the global electricity access situation in order to establish the extent of off-grid project coverage today and the remaining task to achieve universal electrification. Second, since the project development life-cycle reoccurs throughout the thesis, an overview of a generic approach for an off-grid electrification project development is described, informed by the author's field experience. To the second point, the level of sustainability of off-grid projects, this is addressed comprehensively in Chapter 3.

At the time of this research, 771 million people live without access to electricity [1]. Globally those that are under-served come from developing countries and tend to be the relative poorest populations within those countries. Nearly 579 million and 155 million are without access to electricity in Sub Saharan Africa and developing Asia respectively as shown in Table 1.2 (Source: [1]). Rural population in developing countries make up a disproportionate number of those without electricity, at around 77.8% of the total without access shown in Figure 1.1 (Source: [1]).

Electricity access is a critical input for many areas of life and enables many development outcomes. The global development framework, including the UN sponsored Sustainable Development Goals (SDGs) and in the previous iteration, the Millennium Development Goals (MDGs), widely recognized that energy was a cross-cutting issue [17–19]. Achieving universal access to modern energy has become a major international end on its own right through the United Nations Sustainable Energy for All (SE4ALL) initiative. In SE4ALL, UN Secretary General Ban Ki-moon said "Energy is the golden thread that connects economic growth, social equity, and environmental sustainability" [20]. The goals of SE4ALL include ensuring universal access to mod-

Table 1.2: Electricity Access in 2019, by Region (Adapted by author from: [1])

Region	**Population without Electricity** *millions*	**Electrification Rate** %	**Urban Electrification Rate** %	**Rural Electrification Rate** %
WORLD	771	90	96	85
Africa	579	56	81	37
North Africa	< 1	> 99	> 99	> 99
Sub Saharan Africa	578	48	76	29
Developing Asia	155	91	99	94
China	< 1	> 99	> 99	> 99
India	6	> 99	> 99	> 99
Indonesia	2	> 99	> 99	99
Other SE Asia	36	91	98	85
Other Developing Asia	112	79	88	74
Central & S. America	16	97	99	87
Middle East	19	92	98	77

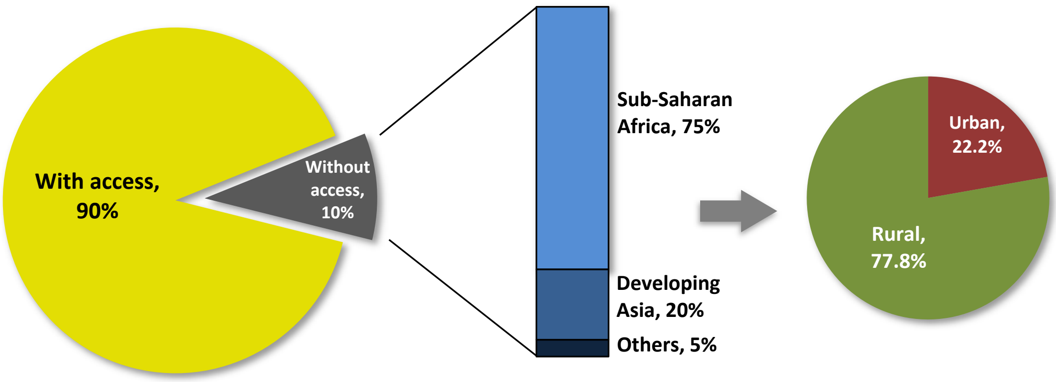

Figure 1.1: World Electricity Access by Region and Rurality, 2019 (Adapted by author from: [1])

ern energy services, doubling the global rate of improvement in energy efficiency, and doubling the share of renewable energy in the global energy mix [19].

These global goals are clearly important to general economic development, and in regions where lack of access is prevalent, to the eradication of energy poverty [21]. *Energy poverty* has been defined as "the lack of adequate modern energy for the basic needs of cooking, warmth and lighting, and essential energy services for schools, health centres and income generation" [18]. This definition points to the many facets of life where energy access has a fundamental role to enable.

Efforts to capture the relative importance of energy towards development have progressed to various multi-dimensional indices. The Human Development Index (HDI),

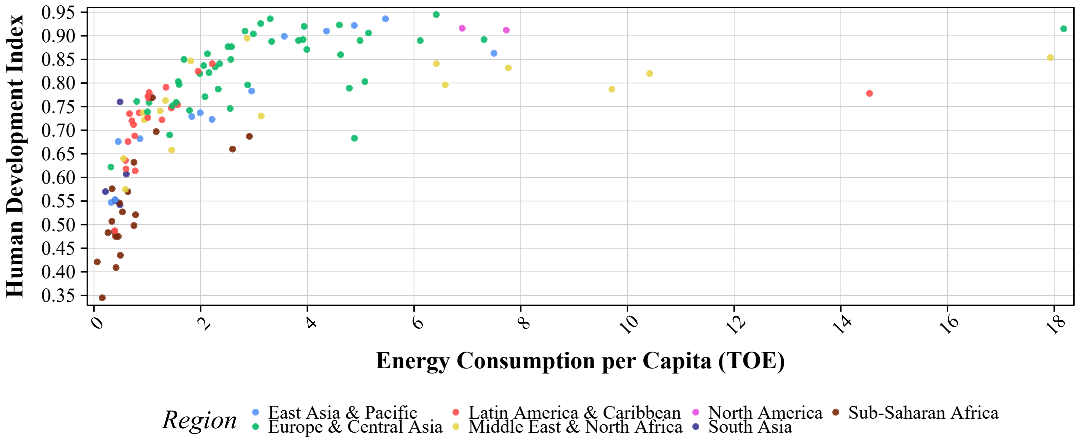

Figure 1.2: HDI and Energy Consumption, Per Capita, 2013 (Adapted by author from: [2, 3])

measures level of development through access to human capacities and has been shown to be statistically linked to energy access [1] [22–24]. A linear regression of the relationship of HDI to Electricity access had an R^2 of 0.811, indicating a remarkably close correlation [25]. Although a causal relationship between access to electricity and development outcomes is difficult to determine, they are undeniably linked.

Other development indexes, such as the Global Multi-Dimensional Poverty Index (MPI) actually include electricity access as sub-indicator [26]. In the 2012 IEA World Energy Access report, a new index called the Energy Development Index was created and is based on four sub metrics: household access to electricity, household access to clean cooking facilities, public service access to energy, and access to energy for productive uses [27]. The close relationship between the HDI and energy consumption can be clearly seen in Figure 1.2 (Source: [2, 3]). Particularly for the range of 0 to 1.5 TOE/capita, a range populated predominately by SSA countries, a clear improvement of HDI is associated with higher energy consumption.

In recent years, the understanding and measurement of what it means to have access to electricity has become more granular, taking in the consideration of the quality of customer's supply connection. Rather than a binary measure (grid access or not),

[1] Sub-metrics of the HDI include life expectancy, years of schooling, and gross national capita as opposed to the conventional approach that depends solely on GDP/capita

the new measure can characterise the quality of access for those that live in a continual state of shortage and rolling blackout (e.g. 10 hours a day in Nigeria) as well as those with very small supply (power capacities in the tens and hundreds of Watts). ESMAP has re-defined electricity (and other energy) access to include a multi-tier matrix framework where tier 0 corresponds to no access at all and tier 5 is equivalent to extremely reliable grid access [7][2]. The revised scale provides a more representative picture of how households, communities and businesses are accessing energy in developing countries facilitates more precise policy making. In Figure 1.3, the highest Tier 5 access, common to the developed world, is much less prevalent than previously thought [4]. It is also perhaps indicative of the increasing awareness of the practitioner community of impact various levels of access have and the availability of technological solutions which can be targeted towards a particular tier of access.

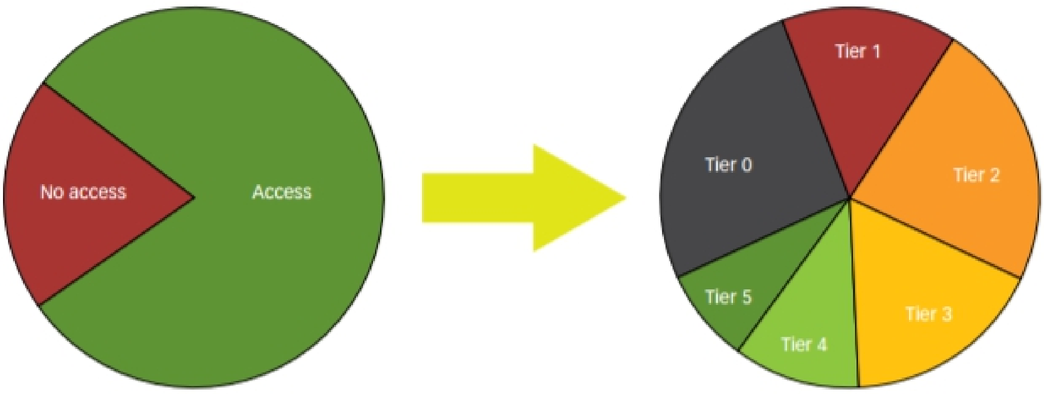

Figure 1.3: Binary vs. Multi-tier Access to Electricity [4]

The development community has recognised that for energy access to be effective, it must match affordable solutions to the consumer needs [28]. Rural populations in developing countries not connected to the grid depend heavily on local energy sources such as wood fuel and charcoal for most of their energy needs. Cooking, is generally the most energy-intensive activity of the household and accounts for about 90% of all household energy use [29]. Nonetheless as technology prices reduce and renewable electricity becomes cost competitive with traditional fuel sources, the transition to

[2]Described in more detail in Section 1.2.3

modern fuels and electricity is an ongoing trend representing both an opportunity development that includes cleaner fuels, such as renewable-based electricity, and a key step towards modern lifestyles for the community.

1.2.1 Top-Down vs. Bottom-Up Experiences in Electricity Access

Given the scope of the challenge of providing electricity access to 771 million people, a mix of solutions must be considered, from conventional means such as centralised grid extension to deployment of off-grid small scale renewables. The approach in developing countries may likely follow a different path than that of the developed nations, where much of the received knowledge on grid development scenarios have been documented. Off-grid options are becoming increasingly viable, especially for lower tier access. In 2016 Practical Action [30] calculated minimum costs for electricity access options for four rural communities in Sub Saharan Africa and found that micro-grids, stand-alone power systems, diesel mini-grids were the most economically viable and most reliable in some circumstances. Although the calculated price per kilo Watt hour (kWh) for stand-alone options varied from USD \$1.26 - \$1.48, while for grid extension was between \$0.41 - \$1.05, the study concluded that decentralized options can be "superior to the grid" where downward price trends are present (solar) and timeliness of delivering a solution is important [30, p.68]. Levin and Thomas use local market system prices to calculate cost-effective deployment of Solar Home Systems (SHS) to achieve the ESMAP energy tiers in Senegal, Ghana, and Kenya [31]. In almost all cases tier 1 access (3 - 50 Watt systems with 12 - 200 Watt-hours of storage) is most cost-effective with SHS versus centralised generation and in Kenya, SHS are becoming more competitive for tier 2 access (50 - 200 Watt systems with 200 - 1000 Watt-hours of storage).

In addition to the economics, the centralised approach faces many obstacles that have served to impede progress. These may include poor institutional frameworks, low productivity, low existing infrastructure and other capital stocks, poor fundamental macroeconomic management, remoteness of populations and difficult terrain, and low political willingness/ability to change policy [32]. Rural electrification is a relatively non-profitable investment where the remoteness of the customers, low density and minimal consumption level mean the cost per capita to connect is much higher than urban locales or dedicated industry [33]. Replicating the model of past grid development, that have evolved to an open-access grid, highly capitalised, deregulated, and centralised markets, will require significant progress against these obstacles first. Institutional development needs ample political engagement and support of the industry to, for example, liberalise pricing or to privatise an industry dominated by an inefficient nationalised company – it is a slow and sometimes gruelling process. Despite USD $350 million from the Millennium Challenge Corporation in 2011, the ongoing process of grid extension has only achieved 5% rural electricity access [34, 35].

Meanwhile, the international development community and local efforts to develop off-grid energy access, often through NGO assistance, have continued to implement projects at various levels and with some success. Although off-grid approaches have been cited as “inferior” [25] or “intermediate” [36, p.3], the solution has the advantage of being relatively quick to implement. Comparing to top-down strategies where technical assistance is provided, such as through the World Bank or ESMAP, to national entities (the energy regulator or nationalised power supply company), the local NGO effort entry point has been communities and entrepreneurs [37]. This approach is fundamentally different as the interventions must take the national framework as a given. The politics, laws and regulations, technology, supply chains — aspects that make up the institutional arrangement — are typically not meant to change as a result of the intervention. Instead, these projects are undertaken *in spite of* the challenges due to the institutional arrangements currently present because there is a strong will of communities and supportive NGOs to champion the projects. Funding and mandates of NGOs address the needs of the most impoverished and focus on development areas that are complementary, not duplicative, to local government’s own initiatives. For electricity access goals, this means targeting relatively remote areas where grid extension is unlikely and where there are otherwise no other means to achieve rural electrification. Of course, this focus amplifies the challenge due to the weak institutional arrangement and rurality of the intervention.

Considering the gains in electricity access made over the last decades, it is relevant to consider the context of those gains. The efforts within China, which has achieved a rapid rate of rural electrification, in terms of sheer numbers of people gaining access, are truly impressive. In the early 1990s the country provided electricity access to nearly 500 million people, led by government and a sympathetic institutional context [38, 39]. In contrast to many current off-grid efforts that can be characterised by their decentralised nature, the Chinese case demonstrates off-grid electrification success due to strong local engagement and a strong central government commitment over a considerable period of time [40].

India is another country which has made strides towards achieving rural electricity access and in recent years has had an acceleration of progress. Reportedly, 100% of villages have been electrified by 2018 [41]. India's rural electrification history extends to the late 1950s when focus began to shift towards village electrification. Early efforts were focused on pump system electrification, and general village electrification only became more prevalent in the 1970s [42]. Since the late 1990s and early 2000s the emphasis on rural development through electrification has further accelerated efforts with a series of legislative acts and central and state government support. Notably, these include the establishment of institutional structures (e.g. Ministry of Power, Ministry of New and Renewable Energy, and Rural Electrification Corporation), electrification requirements for public facilities, and considerable funding schemes. However, despite a substantial institutional structure and recent progress, it is far from achieving universal access and has serious sustainability questions. The WEO estimates over 240 million Indians (and 25.6% of the rural population) [43] lack access to electricity even though almost all the villages nominally have 'access' – clearly the distinction of access at the village does not equate to 100% access by households [41]. Furthermore, it has been noted that the model has several long-term risks: under-estimated original ongoing costs, red tape, potential for unreliable service quality, and insufficient revenue generation [42].

In many developing countries, a similar strong central government role is not easily realised, nor are the policies in place that might enable further development of the sector (as shown in the Figure 1.4, source: [5]). Enabling regulatory policies and fiscal incentives or public financing have many gaps, and even those countries that do higher policy coverage (such as Nepal) still struggle to enact change. As a result, the replication of the Chinese model of success, or the Indian substaintial yet strained progress, seems improbable without first addressing structural change at the national level.

COUNTRY		REGULATORY POLICIES							FISCAL INCENTIVES AND PUBLIC FINANCING				
	Renewable energy targets	Feed-in tariff / premium payment	Electric utility quota obligation / RPS	Net metering / net billing	Transport obligation / mandate	Heat obligation/ mandate	Tradable REC	Tendering'	Capital subsidy, grant, or rebate	Investment or production tax credits	Reductions in sales, energy, VAT or other taxes	Energy production payment	Public investment, loans, or grants
LOW INCOME COUNTRIES													
Burkina Faso								O		O	O	O	
Ethiopia	O				O						O		O
Gambia	O										O		
Guinea	R										O		
Haiti	R												O
Liberia	R										O		
Madagascar	R										O		
Malawi	R				O						O		O
Mali	O				O						O		O
Mozambique	O				O						O		O
Nepal	O	O					O	O	O	O	O		O
Niger	R										O		
Rwanda	O	O						O		O	O		O
Tanzania	O	O							O		O	O	O
Togo	R										O		
Uganda	R	O						O	O		O		O
Zimbabwe	O				O						O		O

O EXISTING NATIONAL (could also include subnational) ★ NEW (one or more policies of this type) ★* NEW SUB-NATIONAL
● EXISTING SUB-NATIONAL (but no national) R REVISED (one or more policies of this type) R* REVISED SUB-NATIONAL

Figure 1.4: Renewable Energy Policies in Low-Income Countries [5]

1.2.2 Investment and forecasts of off-grid penetration

There are many strong supporters of off-grid energy solutions for developing countries who expect that small-scale renewables based options will play a major role [36, 44]. For rural populations with low density and separated from urban centres by challenging terrain, distributed generation is the only realistic and immediate solution available. The IEA has estimated that to achieve universal electricity access by 2030 will require a nearly \$50 billion per year investment in their Energy for All scenario [38, p.481]. In this scenario, 70% of new rural electricity access is expected to be in the form of mini-grids or with small, stand-alone off-grid solutions where it is assumed that grid extension is too costly [38, p.483].

The likelihood of the IEA Energy For All scenario coming to fruition appears plausible because of several factors: the proliferation of low cost electricity supply technology (solar photovoltaics, Lithium-based battery systems, low cost small scale power regulation electronics), availability of highly-efficient consumer appliances, and excitement over a shift in focus to small-scale, consumer or community level implementation, rather than centralised grid investment. Bazilian et al. review the measures and current status of solar photovoltaic economics including the concepts of levelised cost of energy (LCOE) and 'grid-parity' as they observe a dramatic reduction in solar module prices since 2008 [45]. By 2010, manufactured prices fell below \$1/W USD, the point where grid parity could be achieved. With a long-term learning rate of photovoltaics of around 20%, which relates the price of PV modules compared to production levels over time, it is likely that the technology will continue to become more competitive in the future [46]. Due to these global economic trends, it is widely held that decentralised solutions will be the most viable option for securing electricity access goals [47–51].

The advances of the supply side have been matched by equally important technological advances affecting demand for electricity. The proliferation of affordable, highly energy efficient, and highly desirable consumer devices such as mobile phones, music players, light emitting diode (LED) lighting has now thoroughly extended to developing country markets [52]. The economics in individual households to replace obsolete lighting with new generation LED lanterns is compelling. Despite a higher initial costs, payback periods have been under one year for a decade [53]. Organisations such as Lighting Africa have led improvements in quality standards to ensure more robust products are reaching the market [54]. Innovative finance and use of digital currency in Rwanda and Kenya now allow for payments to be made over mobile phones for items such as basic lighting, a radio, and even larger consumer goods such as TVs and refrigeration [55]. The technological change is a great benefit for individual consumers, where cleaner technologies can replace unhealthy or unsafe energy sources, for example with submersible LED fishing lamps replacing kerosene alternatives [56]. Many of these new developments stem from important worldwide trends, such as massive competition among the global mobile handset manufacturers targeting secondary growth markets in developing countries, and key innovations such as the commercialisation of lithium-based storage technology and LEDs. The International Finance Corporation, which advocates commercial solutions to solve the electricity access problem, estimated a potential yearly market of USD $37 billion if traditional energy uses were transitioned to modern options in developing countries [57].

As a result of the revitalised global impetus to achieve universal electricity access, favourable economic conditions for small scale renewable generation technology, and electricity using consumer devices, off-grid options are more plausible then ever as the solution of choice for future electricity access. When current estimates of off-grid penetration for new energy access is converted into persons, 77.8% of 771 million or 617 million are in rural areas. An estimated 70% of these, or 432 million, are expected to be electrified with an off-grid source, which represents an enormous market and need. It also provides clear mandate for the focus of this research. However, as is discussed in detail in Chapters 2 and 3, the track record of sustainability of many projects is in question, which poses a major risk to this investment achieving its goal.

1.2.3 Classification of Off-Grid Electricity Projects

The sustainability framework in this thesis argues for a revised approach to the implementation of off-grid electricity projects in developing countries. It is therefore important to identify the types of projects for which this framework is applicable. This section describes the project development life-cycle and presents classifications of projects based on technology, sizing, and functionality.

Project Development and life-cycle

Off-grid electrification projects are viewed in this thesis through the lens of a life-cycle involving major stages such as concept, design, development, implementation, and aftercare as shown in Figure 1.5 (Source: Peter Dauenhauer). Key sustainability considerations throughout the development process that are featured in this thesis are highlighted in yellow.

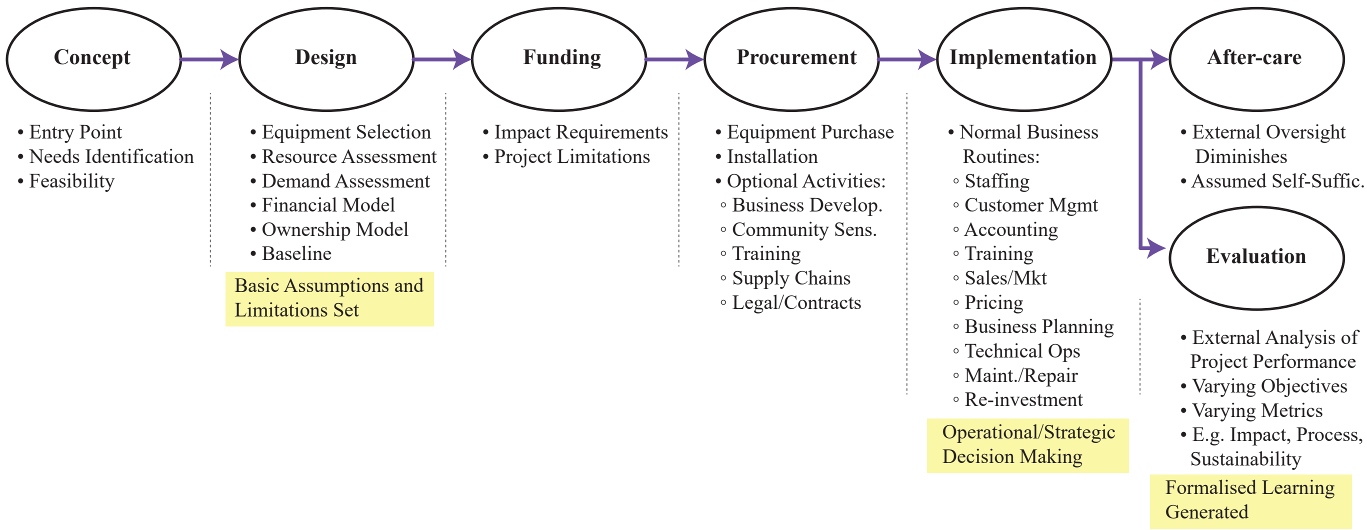

Figure 1.5: Generalised Project Development Stages

The Project **Concept** development is the entry point for a project and is initiated by many potential sources. Bottom-up sources include communities or community groups, local enterprises, NGOs working alongside communities, or sub-national administrative divisions (for example a district or municipal led initiative). Examples of top-down sources are national government, external governments, bi-lateral or multi-national funders, or utilities. The project concept entails an identified need or opportunity and, at minimum, implies an assumption of the project feasibility that has an acceptable level of risk. More advanced feasibility activities include resource assessment, demand assessment, business development, and socio-economic impact studies.

Project **design** determines critical inputs to the technical equipment selection, financial model, organisational arrangement, and relationship with the local community. Power generation technology is selected to make optimal use of the available energy resources that are required to meet energy demand expectations. The local geography determines the feasibility of various options for power distribution. Generally, more dispersed populations require standalone systems, micro-/mini-grids whereas areas with a relatively dense population and a potential for a larger load will be better suited for grid extension. In addition to the technical design, accompanying design is needed for the ownership model, financial model, training plans, and community involvement, if relevant. Since there is often a distinct lack of basic data in these areas, data collection campaigns are needed to determine aspects such as willingness and ability to pay, local energy resources (i.e. to a greater degree of granularity than is available from general sources), community mapping, and environmental assessments. Many projects in developing countries are also funded on the expectation that a specific impact is achieved through the project, for example “increased livelihoods”, so baseline studies are conducted for use in quantifying the starting point, prior to the implementation. It is during the project design stage where many of the basic assumptions and limitations of the project are determined. For example, equipment choice is dependent on predicted load demand and level of renewable resource; these choices may also be difficult or expensive to change over time if the underlying assumptions turn out to be inaccurate.

The **funding** model creation connects the proposed system design and expected impact to funders. Historically, funding electricity access projects has been dominated by bi-/multi-lateral donors which usually require a robust reporting framework to gauge the effect of the project. Hence a project may need to meet certain criteria to be acceptable to these funders. For example, it may be a requirement that the project involves a specific renewable energy technology, ensures equal participation of women in the project, or targets communities with a certain poverty level. Private funding for such projects, in contrast, is in its early stages due in part to the low returns, ongoing sustainability issues (and lowered risk appetite), and lack of general knowledge from conventional financiers on off-grid business models. Therefore, many projects tend to be funded on a grant basis where initial capital costs are wholly covered by the donor and the focus of the project is on maintaining service as the assets age.

Procurement consolidates all project components and installs equipment on site. The use of certified installers with a track record and a procurement process that is transparent is critical to ensuring the installation is as designed. Component selection needs to be monitored where renewables markets are less developed as there is in some cases wide availability of non-genuine components that have a poor manufacturing quality. Additionally, procurement initiates complementary activities at the community and organisational level, were necessary, including community sensitisation, marketing and sales, business development, training, setup of supply chains, and legal/contractual arrangements.

As shown in Figure 1.5, **Implementation** (or **Normal Operations**) of a project occurs after its commission and is an ongoing state whereby normal business routines occur: employment of staff, customer management, accounting, training, sales and marketing, pricing, business planning, technical operations, maintenance and repair, and re-investment for up-scaling. The ownership model and experience of the project will determine emphasis on each routine and only the most advanced will excel at all aspects. A basic, minimalist community owned model that depends on volunteer staff may have limited scope for keeping detailed accounts and conducting regular business analyses such as cash-flow analysis. It is in the implementation phase of the project where operational and strategic decision-making occurs based on the day-to-day experience of the project.

After-care and Evaluation Activities are optional and dependent on the ownership model and project funding. Most projects are designed under the assumption that sustained operation, in some cases indefinitely, will occur. However, additional financial support resources may be available, during procurement and shortly thereafter, for the project to work with an external organisation to build capacity and monitor its performance. After this funding is spent, external oversight diminishes, and the project enters an *after-care* phase whereby self-sufficiency is assumed. Another interpretation of this state is just normal operations without additional support. *Evaluation* is part and parcel of donor funded projects during which external evaluators gather data from the project and offer feedback, guidance, and analysis of the project. Since evaluation is costly to conduct, inclusion is not consistent. However, it is primarily in the evaluation stage where much of the formalised learning has been gathered. The choice of evaluation metrics are dependent on evaluator's objective and nature of the project; for example metrics can include: number of pupils at a particular school, kilo-Watt hours served, households connected to system, or financial performance indicators of the project. Additionally, the intention of the evaluation can vary from an objective

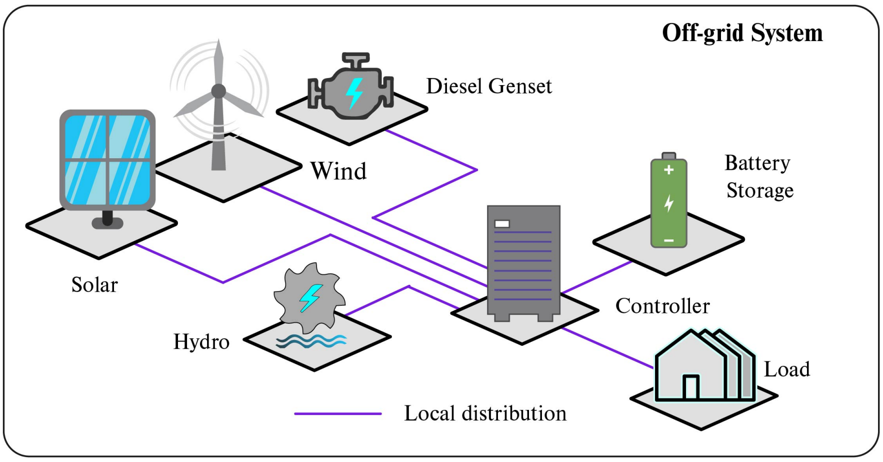

Figure 1.6: Major Components of a Typical Off-grid System

review of the project progress against its baseline to a review of the process of the intervention (which resulted in the project) or a sustainability evaluation.

Overview of Technical Classifications of Off-Grid Projects

At a technical level, an off-grid electrical project involves the deployment of power generation, distribution, control and storage technology in an autonomous manner. A typical arrangement of an off-grid system is shown in Figure 1.6. This contrasts from a central grid which involves large scale power generation, high-voltage transmission, advanced control and protection of equipment, and regulated power supply. Most developing countries will have a central grid but often this will only supply urban and industrial centres.

Off-grid systems can be classified in various ways: by generation technology, by generation size, or by functionality. IRENA has specified five levels of off-grid systems based on generation sizing, capabilities and complexity including stand-alone systems, pico-grid, nano-grid, micro-grid and mini-grid as shown in the Table 1.3 (Source: [13]).

The spectrum of technological options for off-grid systems is relatively wide as the scale of a micro-grid can range from a collection of a few connected households, completely isolated from the centralised grid, to a medium scale scheme micro-grid that connects thousands of customers as shown in Figure 1.7 (Source: adapted from EUEI PDF Mini-grid Policy Toolkit [6]). Furthermore, there has been an ongoing discussion

Table 1.3: IRENA Classification of Off-grid systems [13]

	Size (kW)	**Capability**	**Complexity**
Stand-alone systems	0 - 0.1		
Pico-grid	0 - 1	•Single controller	
Nano-grid	0 - 5	•Single voltage •Single price •Controllers negotiate with other across gateways to buy or sell power	•Both grid-tied and remote systems •Preference for DC systems •Typically serving single building or single load •Single administrator
Micro-grid	5 - 100	•Manage local energy supply and demand •Provide variety of voltages •Provide a variety of quality and reliability options •Optimise multiple-out energy systems	•Incorporate generation •Varying pricing possible
Mini-grid	5 - 100,000	•Local generation satisfying local demand •Transmission limited to 11 kV	•Interconnected customers

about the relative merits for developing country applications of DC versus AC micro-grids [58, 59]. Small scale DC-based systems reduce the need for additional conversions and hence have the potential for higher efficiency, but lag behind AC-based systems that have conventionally been cheaper, more familiar with designers and technicians, and have a significantly more developed market for appliances. Tenenbaum et al. estimate switching from AC to DC devices would save 33% on energy consumption and 14% on reduced conversion losses [60].

The technical systems of a project can drive the business model. For maintenance routines, simple, essentially 'black box' solar lanterns can be supported by a limited technical maintenance and well established supply chain for specific vendors [53]. The next level of system complexity, solar home systems require more extensive user training, or more likely a fault-based maintenance scheme, such as was trialed in Zambia [61]. Distributed maintenance schemes, where operators contract maintenance and replacement from installers as required, are being experimented with in Kenya and other countries by BBOXX Ltd, PowerGen and SteamaCo [62–64]. Embedded remote data system data-loggers are becoming more prevalent and assisting with more granular and near real-time maintenance functions [65]. Relatively larger scale off-grid systems often require in-house asset management and maintenance capabilities [66]. Monetisation options become greater with more energy available. Added business acumen is needed manage the various lines of business from productive uses of energy (refrigeration, agricultural processing, etc.) when, as some project choose, these are kept under the umbrella of the organisation itself rather than focusing on direct energy sales only [67, 68].

Generation scaling Classification of Off-grid Projects

With respect to scale, off-grid projects can vary from a small stand-alone solar PV home system or small business of less than 100 Watts to micro-grids capable of providing a near-centralised grid service for hundreds of homes and generating capacity in the hundreds or thousands of kilo-Watts. With this potential range of scale, the economics, complexity, particular technical and organisational arrangements can be quite varied.

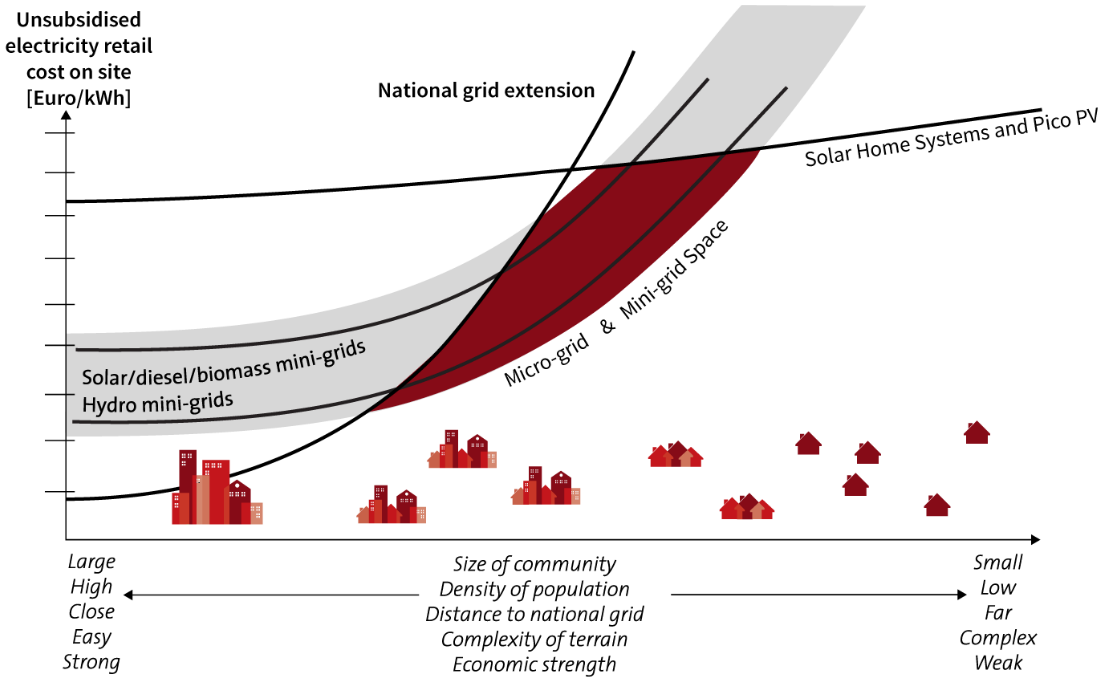

Figure 1.7: Micro-/Mini-grids space compared to alternatives [6]

Hence, while the classification is based on the technical aspect of generation sizing, the complexity, in terms of other factors like organisational requirements, is equally important.

Smaller systems tend to simplify technology options and are driven by affordability limitations and low skill requirements by operators and users. The smallest systems, including rechargeable LED solar-lanterns, and mobile phone charging kits are essentially "plug-and-play" and as such require very little training and no installation, for example [69]. Systems that require installation and maintenance, starting with bespoke stand-alone systems, provide increased capability but require ongoing maintenance. For rural, dispersed populations, these highly distributed options are usually the most economically feasible as they obviate the need for medium- or high-voltage power transmission and distribution.

Scaling up to the tens of kilowatts (or larger) are systems which could be based on a variety of generation technology and will require the inclusion of voltage step-up, limited distribution, power system protection (if even basic), and a capable organisation for managing day-to-day operations and maintenance. These systems are suited for relatively dense loads in geographical areas which are otherwise unfeasible to connect to the main grid.

Functionality Classification of Off-grid Projects

In addition to scale and technology, the functionality of the system can be used to classify the project. In past years, a binary scale of connected (to the main grid) or not connected was used to distinguish electricity access. To this end, ESMAP's Tiered Classification provides a breakdown of level of functionality of a particular system, as shown in Figure 1.8 [7]. The ESMAP is globally applicable and specifies functionality attributes such as power capacity, availability, reliability, quality, and so on — from which a system can be classified. Off-grid systems in developing countries described as solar home systems typically vary between Tier 1 and Tier 3 while mini-/micro-grids vary between Tier 3 and 5.

Using the ESMAP classification, functionality can be derived for a system, whereas IRENA's classification provides additional specific capabilities. For example, mini- and micro-grids can provide a variety of voltages, potentially allow for more advanced tariff structures, optimise multiple generation sources, and may even have capacity to interconnect with the main grid. At the extreme other end, the simplest off-grid devices may be limited to specific usage applications (lighting or mobile phone charging) and strict limits on consumption levels.

Off-grid electricity projects, in their various classifications, are different from other electricity projects conducted in developed countries or grid-extension projects in developing countries. They are often targeted at rural villages with little to no access to financial services, non-existent infrastructure, low technology, and primarily unskilled labour. These factors have prevented conventional grid extension electrification and remain critical barriers to off-grid electrification. Off-grid projects typically face low absolute load demand, low ability-to-pay, geographic constraints and difficult terrain, dispersed populations, and an extremely small industrial base. In addition, unhelpful macroeconomic conditions of the country such as high interest rates, inflation, or access to capital further hinder their success.

Figure 1.8: ESMAP Multi-tier Matrix for Access to Household Electricity Supply [7]

Multi-tier Matrix for Access to Household Electricity Supply

ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
1. Capacity	Power		Very Low Power Min 3 W	Low Power Min 50 W	Medium Power Min 200 W	High Power Min 800 W	Very High Power Min 2 kW
	AND Daily Capacity		Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
	OR Services		Lighting of 1,000 lmhrs per day and phone charging	Electrical lighting, air circulation, television, and phone charging are possible			
2. Duration	Hours per day		Min 4 hrs	Min 4 hr	Min 8 hrs	Min 16 hrs	Min 23 hrs
	Hours per evening		Min 1 hrs	Min 2 hr s	Min 3 hrs	Min 4 hrs	Min 4 hrs
3. Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration < 2 hours
4. Quality						Voltage problems do not affect the use of desired appliances	
5. Affordability					Cost of a standard consumption package of 365 kWh per annum is less than 5% of household income		
6. Legality						Bill is paid to the utility, prepaid card seller, or authorized representative	
7. Health and Safety						Absence of past accidents and perception of high risk in the future	

1.3 Organisation of Chapters

Chapter 1 presented a narrative of current implementation of off-grid projects in developing countries and showed that investment in off-grid projects will be a significant driver of future electricity access projects in the future. However, continued investment is not enough to achieve universal access to electricity in a reasonable time frame. This chapter discusses the classification of a general off-grid project in terms of size, capability, and the context in which they are typically deployed – within a development project – which are critical to understanding the sustainability challenges that they face throughout their lifetime. Finally, the specific motivation of this thesis is presented in full: that the sustainability of off-grid projects is a complex problem requiring, first, a better understanding of the factors of success and their interrelationships and, second, a new framework for learning about the impact of sustainability interventions that are tested.

Chapter 2 addresses the inconsistent approach to defining and measuring sustainability by arguing for a new definition of sustainability that responds to weaknesses found in existing approaches taken in the literature. A *project-centric* view of the definition is developed in distinction from popular *outcome-centric* definitions that, in the view of this thesis, have created a degree of confusion when applied in the practical sense to sustainable project design or evaluation. Several prominent literature sources are critiqued: sustainability toolkits, sustainability indicators, and system design optimisation. The approaches are analysed with respect to their contribution towards understanding project-centric sustainability. Although each source serves a purpose in ensuring long-lasting sustainability of projects, each have weaknesses that ultimately leave a gap that projects fall through. Nonetheless together, and with the novel improvements suggested within this thesis, they are the building blocks of a framework for sustainability and justify the latter sections of the thesis.

Chapter 3 provides the evidentiary background of the levels of sustainability of off-grid projects. An extensive analysis of projects drawn from the literature include a survey of off-grid project sustainability experiences worldwide, and an in-depth study from three individual projects involving Non-Governmental Organisations (NGOs) in which the author of this thesis was involved. The review confirms a wide range of sustainability challenges facing projects. An analysis finds mixed sustainability performance overall with over 80 distinct sustainability issues, and perhaps more importantly, an inconsistent approach to defining and measuring sustainability itself. It is these challenges and the gaps found in the current approach to designing projects for sustainability at which this thesis is targeted. The chapter also highlights the importance of the operational phase of a project towards sustainability. It is shown that there is a complexity within the connections of available information, decision-making, and operator actions to ensure ongoing sustainability.

Chapter 4 develops a computer simulation of an off-grid stand-alone PV project to demonstrate the value of an informational layer and decision-making throughout the project life-cycle. Simulation design choices are discussed with respect to the implications for project sustainability, which are then contrasted versus techno-economic optimisations. The simulation is unique as it models a wide range of mechanisms not usually present in simulations including: organisational skill management, social and economic interactions with customers and the wider community, and operator decision sets defining the strategic decisions they make affecting sustainability. An extensive discussion of the results of the simulations follow. These are used to provide new insights into the relationship between project design, ongoing operation, and learning phases. Additionally, important implications on the modelling approach commonly taken in the literature are summarised along with the role of indicators for practitioners undertaking future projects.

Chapter 5 develops the implications of the research and focuses on making them meaningful for specific stakeholders: project designers and implementers, practitioners, researchers, and finally, policy makers. The chapter proposes a sustainability framework for off-grid projects in developing countries. The framework is expressed as a process map that captures the sustainability planning and implementation at each stage in the project life-cycle. Through the framework and discussion, the chapter responds to the gaps identified in the literature by connecting them to the work done in this thesis. Although the novel analysis conducted up to this point focuses on specific details, this chapter stretches the analysis to the high level perspective of: how do the stakeholder enact systematic change in project development with the goal of improving sustainability on each iteration? The chapter finishes by proposing extensions to the research in the thesis to address the identified weaknesses and address remaining gaps in the literature.

The concluding Chapter 6 draws out the novel learning, insights, and conclusions from this research.

1.4 Contributions of this Research

The overarching objective of this thesis is to draw out and propose approaches to systematically address sustainability issues affecting off-grid projects in developing countries. The contributions, listed below, are relevant to off-grid project designers, implementing organisations, policy makers, and the academic community working in the area of energy access. The contributions (shown as a list in Table 1.1 are complementary to each other and build towards the high-level objective:

1. A consistent approach to achieving sustainable off-grid projects requires a consistent definition and use of the term 'sustainability' amongst stakeholders. This thesis provides a **project-centric definition of sustainability** so that it can be applied to off-grid projects in a relevant way. To do this, the origins of existing definitions in the literature are investigated and a new definition is synthesized. The term 'sustainability' is ubiquitous, has many competing meanings, and even in the context of off-grid energy projects in developing countries, is often used imprecisely. Although stakeholders involved in these projects inherently desire the continued survival of their projects, the inability to adhere to a single workable understanding of the term undermines the ability to learn about and improve it. This contribution answers the questions: *What is sustainability in the context of off-grid electricity projects in developing countries? How can sustainability be measured at a project level and meaningfully compared?*

2. An **extensive review and comparison of defacto standard methods used in project sustainability, including: techno-economic optimisation for sus-**

tainability, indicator frameworks, and sustainability toolkits is undertaken to capture the roles these sources play in the life-cycle of projects, specifically as it pertains to sustainability issues. This thesis finds inconsistencies in these approaches toward understanding sustainability which manifest in differing design methods, monitoring and evaluation methods, and the learning which is produced from successive projects. This serves to undermine their relevance when applied to the context of off-grid project sustainability. This thesis argues that these inconsistencies amount to gaps in what is otherwise a foundation for a sustainability framework and seeks to recast these sources more squarely into the context of off-grid project sustainability. The review of each approach can be considered a novel contribution in its own right. This critique lays the foundation for the modelling, development of a systematic sustainability conceptual framework, and discussion which follows. The approach has been to provide actionable recommendations whenever gaps are identified. Specific findings within each approach are enumerated in Table 1.4.

3. Establishing a literature review of off-grid experiences in developing countries is undertaken to produce an **evaluation of the current levels of sustainability**. Many projects are poorly documented when it comes to sustainability. The available literature has largely taken the form of case-studies and in many cases these do not expressly address sustainability or define a method for sustainability evaluation which would allow general comparison. Instead, judgments are made depending on author discretion. The review identifies the sustainability issues identified in the literature, organises the issues by sustainability category and conducts an analysis on the concentration of category (economic, organisational, technical, social, environmental and external) by authors. The analysis establishes a wide range of problems: 84 distinct issues are identified and an average of 7.5 issues identified per article. The projects that are included cover a range of projects worldwide and both of older vintage and more recent projects. The analysis also finds evidence that sustainability evaluations currently tend to concentrate their coverage of issues into one category. This supports one of the motivations of this thesis that sustainability weaknesses are still a major issue and there is not a general consensus on how to ensure sustainability.

Table 1.4: Sustainability Literature Sources

Approach	Gaps	Recommendations
Sustainability Toolkits	• Limited evidence base and focus on best practice, or successful projects, rather than sustainability problems • Over-dependence on 'sustainability -by- design' culture • Ambiguity of sustainability factors within individual and between toolkits • Poor definition of the interrelationships between sustainability factors as well as dynamic effects	• Expand evidence base to consider a wider range of projects, and project sustainability issues, including problematic cases • Improve guidance on measurement of objective sustainability factors • Emphasize sustainability guidance that occurs in the operational and evaluation stages
Sustainability Indicators Frameworks	• Overemphasis on sustainable development, outcome-centric indicators • Insufficient justification of relevance of proposed indicators	• Utilise base criteria framework by Ilskog comprised of five themes – simplicity, transparency, robust, comprehensive and fair [10]. • Utilise scoring rubric to increases objectivity in sustainability scores, proposed originally by Katre and Tozzi [70]. • Strictly separates project-centric sustainability indicators from aspiring project outcome/sustainable development indicators, proposed first by Bekker and Gaunt [11]. • Use absolute scales rather than relative scales to combat out-of-sample relevance of sustainability evaluation results, raised by Lillo et al. [71].
Techno-economic Optimisation	• Overemphasis design phase sustainability issues • Major simplification of non-technical issues that are nonetheless important for sustainability	• Integrated model incorporating important elements from all sustainability factors • Incorporate relevant operator and customer decision-making • Model sustainability issues that arise during the operational phase of a project

4. A **novel modelling approach for sustainability** of off-grid electrical projects in developing countries is developed and used for the simulation of a project life-cycle. The novel features include an operator and customer decision-making framework, incorporation of a wider range of sustainability categories (adding social and organisational components), and the model's applicability to the operational phase of a project. The model simulates 23 scenarios of an off-grid solar PV project over a 20-year project life-cycle. With an abbreviated set of project-centric indicators, the model demonstrates the importance of adopting indicators that are utilised during all phases of a project. The implications extend beyond the model and its immediate results; use of an informational layer and consideration of sustainability issues that arise during the operational phase can be critical for project success. The analysis argues for an iterative design process prior to field deployment that increases the likelihood of sustainability. Additionally, by coordinating the use of indicators in the design, operations, and evaluation phases of a project, the means for systematic learning around sustainability can be achieved.

5. A **sustainability conceptual framework** is developed, culminating from earlier contributions, which significantly extends the foundational components identified in the literature. The framework proposes linking the stages of a project life-cycle (design, operations, and evaluation) through project-centric sustainability indicators. Comprehensive consideration of all sustainability factors occurs at each stage. During the project design stage, indicators are used together with advanced simulations to predict sustainability and subsequently revise the design. During the operations stage, the indicators are needed to make operational decisions to improve the ongoing sustainability. During the evaluation stage, time-series data that include the indicators, can be used to evaluate the current sustainability as well as the validity of underlying assumptions such as impact of price changes or service availability on community acceptance of the project. A learning stage is proposed and is relevant when considering the cycle of learning from one project to the next. Here, the best-practices are captured, analysed, and synthesised into toolkits. Unlike past iterations of toolkits, the concept of the toolkit is improved by incorporating synthesised learning from comparable projects –

data-sets that are linked to the very indicators that were used throughout the project's life-cycle stages.

Chapter 2

Understanding Sustainability

This chapter is aimed at investigating the “sustainability” of off-grid projects in developing countries. While primarily a literature review that explores the origins and different perspectives from the literature, the chapter offers several contributions that extend concepts in the literature.

The review is centred on three main sources that touch on project level sustainability (outlined in Table 2.1). These include **toolkits** targeted at off-grid projects, **indicator and evaluation frameworks**, and **techno-economic optimisations**. Throughout the project life-cycle, from conception to end-state (be it failure or continued operation), these sources play a critical role in ensuring and judging a given project’s level of sustainability. It is argued that while each source demonstrates an important facet of how the term is understood and used, they lack consistency in usage that leads to challenges when trying to formally capture project sustainability, much less actively address it. The literature review is intended to be constructive by identifying the valuable elements of each source that can be applied at a project level while noting and weaknesses in the method. Table 2.1 summarises the overall role of each literature source.

Table 2.1: Sustainability Literature Sources

Source	**Description**
Toolkits	Practically oriented guides to assist the project planning, design and implementation of a sustainable off-grid electricity project. Existing and prominent toolkits are based on institutional knowledge gleaned from a selection of case studies or based on iterative project experiences.
Sustainability Indicators Frameworks	Designed to enable a systematic and quantitative evaluation element for projects and programmes. Indicators require a layer of data gathering to be implemented alongside projects/programmes in order to be effective. Captured indicators are combined into an index to give the sense of the current project sustainability levels relative to other projects.
Techno-economic Optimisation	Modelling of physical systems to optimise system sizing and technology selection. The optimisation function is typically to minimize net present costs of assets with reliability and environmental constraints. Available through a number of off-the-shelf software packages or calculated manually. Non-technical or economic elements require extensive assumptions are generally not included.

The chapter starts in Section 2.1, by proposing a definition for sustainability in the context of *project-centric* sustainability. This is contrasted against alternative historical definitions.

Section 2.2 selects off-grid electricity project sustainability toolkits (or simply 'toolkits') that have been prominently published by major development organisations, for critical review. The review identifies gaps and develops enhancements to re-envision the role of toolkits, with respect to project-level sustainability.

Section 2.3 presents and discusses the origins and effectiveness of modern sustainability indicator frameworks to capture project sustainability, primarily through evaluations. Indicator frameworks remain linked to the sustainable development origins (outcome-centric), though some aspects have evolved pragmatically, such as the use of a criteria for the selection of relevant (project-centric) indicators. This section captures the current best practices and argues for improvements to address the identified gaps. Indicator frameworks have the most academic rigour and are a strong foundation to revise the definition.

In Section 2.4, the approach of techno-economic optimisation of system design to ensure sustainability of projects is explored. Software aided design of off-grid projects is now a standard. The approach leans on the technical aspects and ties in financial modelling but requires strong assumptions for aspects (social, organisational, external) outside the technical space of project design. Although the approach provides a convincing result, the remaining aspects of project design that interact with the techno-economic systems remain largely disconnected from modelling. A narrow role of the approach, limited to the laboratory setting, is contrasted against a wider role where other sustainability aspects are more explicitly modelled alongside technical and economics aspects. Current limitations of the approach are identified and provide the basis for the modelling work of this thesis in Chapter 4.

2.1 A Project-Centric definition for 'Sustainability'

This section explores the origins of the term 'sustainability' in the context of electrification. Due to its ubiquitous use in many disciplines, it is necessary to define a working definition of the term "sustainability" here. This is proposed through the interpretations of recent usages of the term that can be applied more readily to the context off-grid electricity access projects in developing countries.

Key Insights from Section

- The popular origins of the term 'sustainability' are global, broad, and unstructured. As a result it is difficult to apply directly to off-grid electricity access projects.
- Practitioners in the domain offer insights on how it can be applied. These add an emphasis on local context, interpret the definition as indicators, and stress self-sufficiency.
- A project-centric definition is proposed that is argued to be more relevant for researching off-grid electricity access project sustainability.

The term 'sustainability' was first popularised by the 1987 Brundtland report: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [72]. At the onset, the term sought to balance environmental impacts with economic development which were often at odds with each other. Sustainability is understood as a long-term and global issue: how to avoid the major environmental catastrophes such as global warming and furthermore how to do so fairly among the differing populations living today and future populations. Seghezzo identifies sustainability as the balance between *intra*generational justices, *inter*generational justice and identity or happiness [73]. Within this usage of the term, 'sustainable development' is closely related; meaning the development of societal systems in such a way to not overly impact the sustainability of the whole system.

This section argues that the popularly accepted definition does not provide enough structure or clarity to be applied directly to the sustainability situation for off-grid electricity access projects. Almost immediately after its introduction, the practitioner base has refined what sustainability means, but it continues to lack the clarity needed for wide adoption.

The challenge is threefold: first, the popular usage is so broad and general that attempting to directly adopt the definition is not practical. Therefore, the broad intentions of the term must be distilled into one which has direct meaning to the domain of off-grid electricity access.

Second, the highly localised nature of any single off-grid electricity access project requires that the local context is emphasised. Therefore, the definition must re-balance the global intentions of the term into one which is directly relevant to local communities which implement the projects.

Third, since projects depend on inputs and support from both local and non-local elements during its design and ongoing operations, external factors must have adequate representation. Therefore, the definition must have the ability to clearly demarcate the internal and external elements that factor into a project's sustainability. It must be flexible in its interpretation since any given off-grid project may have a different relationship between itself and external actors.

Insights from Practitioners

Although the Brundtland definition clearly had implications for electrification, it required interpretation to become practical. To this end, organisations interpreted the definition by defining metrics which, combined, represented sustainability. Examples abound from large organisations including the UN [74] and IAEA [15], to the many researchers and practitioners who composed their own indicators [25,33,70,71,75–81](see Section 2.3 for a review of these indicators). These applications suggest that a gradient of sustainability metrics over relevant factors are required to capture the definition.

Examples of refinement of the term to a local context can be traced to electrification practitioners in the 1990s. Jones and Thompson related the Renewable Energy for African Development Model (REFAD), a programme by the US government to work with Southern African Development Community (SADC) on rural electrification [82]. They revise the Brundtland definition to include an interaction with the local community: "meeting the basic needs of the current generation within their own socio-political framework and resource base, in a manner that enhances their quality of life and respects cultural traditions" [82, p. 105]. In application of this definition, Jones and Thompson stress the importance of the context – sustainability requires local capacity building, end-user involvement, address local needs, include local government, and have local maintenance services. Sanghvi and Barnes similarly stressed the involvement of local communities in the sustainability of early World Bank rural electrification programmes [83]. The insight here is that local considerations must be put on an equal footing as global considerations.

Sustainability has been alternatively conceptualised as "surviving and thriving" which seeks to highlight the self-sufficiency of the project. Louie et al. provide a definition along this vein: "potential for a system or project to endure, build a self-perpetuating capacity within a community, and ultimately reach the end of its pre-defined life span or evolve into another beneficial form" as developed by Louie et al [84]. Similarly Terrapon-Pfaff et al. define it as follows: "*Sustainability* in the present case is concerned with measuring whether the expected benefits of a project… are likely to persist after donor funding has been withdrawn" [85]. Both examples serve to anchor the object of sustainability in the project itself rather than larger units – part of sustainability is achieving a level of project self-sufficiency.

Project-centric Sustainability

Given the refinements captured through the literature a new definition is proposed here that is suitable for research around off-grid electricity project sustainability. At a high-level, a 'project-centric sustainability' definition is an off-grid electricity access project's ability to endure within the local context. Furthermore, the definition has the following characteristics:

- 'Internal' operations vs. 'external' considerations
- Established performance metrics
- Local vs. distant external considerations
- Beneficial outcomes are avoided by default
- No pre-defined end-state

It is instructive to discuss the nuances of these characteristics in more detail. By demarcating what is internal versus external, the subject of sustainability is much more clearly captured. 'Internal' are the project's own organisation and assets while 'external' refers to all other considerations. The ambiguity of the web of associated systems that may influence a project but are *not part of* the project can be separated out. This segmentation is still flexible to organisational arrangements that may differ from project to project or external relationships which can be quite varied.

Established performance metrics refers to the quantity, quality, reliability of power supply and delivery as well as the financial viability of the organisation. All organisations that provide off-grid electricity access can almost universally compare these metrics. They underlay all design and operational decisions an organisation may make. As such, when one compares sustainability of two projects, they are comparing against these metrics. These metrics compare similarly to the ESMAP Energy Access Tiers [7].

External considerations, or externalities, are differentiated between 'local' and 'distant'. All projects are impacted by the context in which they operate. The literature stress that the locality of the project should be emphasised – the community, local social and institutional structures, local politics, and local supply chain are local external considerations. In other words, the proximity of these issues are local. Meanwhile 'distant' external considerations are not proximate but in many cases cannot be ignored. Country macroeconomics, national or international political consequences, global supply chains, and to some extent weather are all examples of distant externalities. Inflationary conditions in a country can deeply impact the operation of a project, even if the project itself is not the cause of the inflation. Whether an external consideration is labelled as local, distant, or not included is dependent on how closely it is related to the internal operations of the project. Local externalities are closely coupled, distant externalities are loosely coupled. Externalities that are not coupled are not included.

Beneficial outcomes of a project include are widely-varied but can include: incomes of the beneficiaries, jobs created, share of women employed, project GHG emissions, and even achievement of specific electricity access outcomes such as street lights supported or schools with lighting. A project can exist, successfully, without achieving many or all of these outcomes. While many projects capture a project's performance against beneficial outcomes as part of sustainability determination, their inclusion is not always justified (see Section 2.3). In contrast, a project can be labelled 'impactful' if achieves its development outcomes. In the cases where the evidence supports inclusion of a feedback-loop, whereby achieving a development outcome improves the project's sustainability versus its performance metrics, then it would be considered a local external consideration.

The intention of stating that there is no predefined end-state or expected evolution for a project is to remove life-cycle assumptions. Moreover, it requires that future forecasts of a project's sustainability are needed. A project is more sustainable *currently* by higher *current* performance metrics. It is more sustainable in *future* states by higher *future*, simulated, performance metrics. In many ways this is an agnostic view of how a project may play out its life-cycle. It makes no judgements as to whether manufacturer design requirements were met or whether the project was decommissioned and replaced with a grid connection, and if that is considered a positive outcome by the project designers or beneficiaries. Comparisons to expectations and value judgements of how a project may ultimately end are a compatible, if separate, discussion that can build on the measure of sustainability.

This proposed definition has several beneficial features which differentiate it and support a practical understanding of the term. First, by utilising established performance metrics, comparisons between projects are more direct since the units and measures can be compared one to one. Second, it provides a structure to modelling efforts which are core to understanding sustainability. This makes it easier to remove irrelevant connections to a project. Internal aspects can and should be modeled in great detail, while external considerations may be handled differently. One can assume that local externalities are likely to be relatively more endogenous to a model of the project – that the project is able to affect these externalities and vice versa. In contrast, distant externalities are likely to be relatively more exogenous – taken as a given and unable to be affected by the project.

Conclusion

This section has demonstrated that the definition of sustainability has seen continual revision since its inception. The Brundtland definition was globally oriented, broad and ambiguous, by design. For use in electrification, practitioners have stressed locality, use of metrics, and self-sufficiency when applying the definition. Building on this direction, this thesis has proposed a more structured definition for use in off-grid electricity access contexts.

The proposed 'project-centric sustainability' definition is an off-grid electricity access project's internal ability to endure and/or survive within the local context. Furthermore, the definition has a number of characteristics which help to make relatively more structured other definitions in the literature. These include demarcation of internal operations versus external considerations, established performance metrics, a demarcation of local versus external considerations, avoiding beneficial outcomes (when establishing sustainability), and establishing how to handle the end of the project lifecycle.

It is argued that the proposed definition more readily supports modelling efforts which go hand in hand with understanding sustainability. Furthermore, it recommends established performance metrics in which to compare project sustainability. The definition is used throughout the thesis: in the remainder of Chapter 3, sustainability experiences are documented and classified, in Chapter 4 a model is proposed which utilise established metrics for project decision-making, and in Chapter 5 the definition is central to the objectives of the proposed sustainability framework.

2.2 Sustainability Toolkits

Concerted efforts to establish templates or guidance documents have been developed in recent years aimed at the consolidation of learning from past projects. These guides, handbooks, manuals, and other equivalent labels are referred to collectively as 'toolkits' in this thesis. Toolkits are framed from the perspective of designer, implementer, practitioner or manager rather than the evaluator or academic. Yet they are a critical link to the learning process from these other perspectives. Toolkits are informed from past experience, leaning heavily on the academic resources and impact evaluations, but with the objective to generalise these results into a repeatable process. Hence, toolkits synthesise project learning and offer a guideline for best practises.

The section has two key objectives. First, this section reviews the content of several prominent toolkits and then discusses how they handle the concept of sustainability as it relates to off-grid electricity projects. Weaknesses are identified which serve as gaps in the guidance. Second, proposed toolkit design features are presented to address the gaps. This is later revisited in Chapter 5 in the development of a more comprehensive sustainability framework.

Key Insights from Section

- Links to the evidence base are limited – particularly on project pitfalls and learning from failures. Successful models are used as supporting evidence for guidance which may not be representative to the generalised project experience.
- Insufficient details exists on the interrelationship of indicators that are used to define and establish sustainability of projects. A lack of internal consistency, or external validation with other toolkits, undermines their value.
- Toolkits target sustainability considerations during the project design stage versus the operational stage. As a result, the dialogue on operational options and ultimately decision-making for practitioners is reduced.

The reviewed toolkits are published by the World Bank [8], AFREA [9], EUEI [6], and GIZ [86–88]. *Why are these toolkits selected*? They are the most prominent and widely cited sources that are publicly available for practitioners and have explicit goals to address sustainability. Though other resources exist, they tend to cater to specific technologies and avoid detailed sustainability content.

2.2.1 World Bank Sustainable Off-Grid Projects Toolkit

Perhaps the most prominent toolkit is from the World Bank [8] and is a 21 page operational guidance note aimed at World Bank staff. Although published in 2008, it remains the most widely cited source. In it, 'Sustainability' is defined as the ongoing "operation of off-grid electrification projects over the long term" [8, 2], a definition consistent to the definition established in this thesis (see Section 2.1). The toolkit is divided into two sub-sections: the first is *Critical Factors in Project Design*, the second is *Guidelines for Off-Grid Project Designers*. Findings are drawn from direct experiences from World Bank projects originating from 19 cited countrywide programmes from the late 1980s to early 2000s and indirectly from a pool of another roughly 40 projects funded by the World Bank that contained off-grid elements.[1]

This review concludes that the World Bank toolkit provides interesting but ultimately diluted generalised guidance and disconnected anecdotes rather than a comprehensive framework that could be practically used for project design. Its stated intention to avoid prescriptive design leaves the guidance around sustainability factors only loosely inter-connected to be of much practical use. Furthermore, the sensitivities of the sustainability factors and model variations are not well defined. In short, the toolkit treats sustainability as a black box which has many ingredients but no clear recipe for success.

The Context

In this section the thrust of the document is to present the World Bank learning around topics that are part of the institutional arrangements the Bank sees as necessary for successful projects. The topics are wide ranging and capture an breadth of experience.

For example, the *comparing technology options* topic considers strengths and weaknesses when use of diesel generators, methods for mitigating intermittent (renewable) resources, matching technology options to geo-spatial population density such as through a centralised generating system or solar home systems, and the need for agnostic treatment of technology.

Under the *Enhancing affordability* topic, the authors discuss the role of subsidies in off-grid projects. In rural areas where populations are considerably poorer than

[1] These include: Bangladesh, China, Argentina, Tanzania, Sri Lanka, Philippines, Mexico, Costa Rica, Chile, Honduras, Tunisia, Nicaragua, Papua New Guinea, Solomon Islands, Vanuatu, Fiji, Marshall Islands, Senegal, and Bolivia

urban areas, the authors frame the argument supporting subsidies to be given for off-grid projects on social-equity grounds and the need to be efficient, targeted, and effective. A range of subsidy rates have been used in World Bank projects, from 10 - 90% depending on the country, for solar home system projects.

A topic on *Business models for off-grid service* promotes private operators as a method to achieve relatively timely access in remote areas versus national utility driven grid extension. Private operators need to be adequately incentivised, supported with substantial technical service, and could be owned and operated through several prominent models: community-based, public private partnerships in coordination with the government, or government contracted rural service agreements which are regulated. Several other subsections with topics continue with experience and practical guidelines.

This first section is a mix of generalised issues and potential options to address them interspersed with tidbits of references from past projects. It specifically avoids any hard prescription of a single *right* approach, espousing design decisions on a case by case basis – "the note does not seek to prescribe solutions for success" [8, p. 5] and "designing sound off-grid electrification is far from an exact science" [8, p. 3].

Where references are presented, these can be quite idiosyncratic: in Argentina a franchise model for rural electrification works because of the country's "long experience with concessions for concentrated electricity markets" [8, p. 15]. In the Philippines, a contracting mechanism for PV system installations was highlighted. This arrangement bundled commercial sales to households, businesses and public institutions with a 5-year maintenance and repair contract with a feature of "non-exclusive opportunity to sell SHS to households" [8, p. 16]. There is no guidance on whether this model could or should be promoted elsewhere. Therefore, the references that are provided can be regarded as useful anecdotes but are not generalisable when considered in future projects.

The general guidance in this section does not formalise the relationships between sustainability considerations and as a result leaves these vague. This is hardly practical. Although sustainability considerations are recognised[2] the effort to draw these together

[2] For example the note says (paraphrased): "[A] range of critical decisions... affect sustainability. These decisions include technology choice, ensuring affordability, social safeguards and environmental

and consider how they may impact each other is absent. An example is highlighted to discuss this issue in more detail.

In the note, guidance with respect to the preference of community-based models is that "isolated areas are unlikely to attract private-sector interest" [8, p. 14]. It then goes on to suggest a need for added "technical assistance in design and feasibility studies, training, and social organization" [8, p. 14] and then cites an example from Nicaragua which installed seven 2 kWp solar battery charging stations. The Nicaraguan project had government investment in the initial costs with users making monthly payments to sustain the finances. The model proved difficult for many users to reliably keep up with and hence an effort to raise farmer incomes followed with hope that this would translate in higher ability to pay for the systems. If one considers this specific experience, the general guidance is insufficient to capture the post-installation sustainability decisions that were made. Conversely if one follows the specific experience, the decision-making around further investment in regional economic development must be better captured into the design/design expectations. Furthermore, neither angle addresses the concurrent issues of: correct level of subsidy, the technology decision-making, type and composition of productive and institutional applications, etcetera – the other generalised topics.

The Design Map

The second section introduces a concise model described as an off-grid electrification project framework for sustainability. This is composed of a design map (see Figure 2.1, adapted from: [8]) and supportive text. It identifies necessary aspects for sustainability for example: practical technology choice, provision of training, community involvement, maximising productive uses. Unlike the previous section, this one is almost entirely generalised.

Both the map and the key success factors [3] provide excellent advice for any off-grid project. Since it is concise and relevant, it is unsurprising that the map itself

considerations, ... taking advantage of opportunities to initiate and enhance productive activities and institutional applications... consider ways to use appropriate business models, determine necessary regulatory actions, and explore opportunities for international co-financing" [8, p. 6].

[3]'Sustainability factors' is used interchangeably with 'success factors'

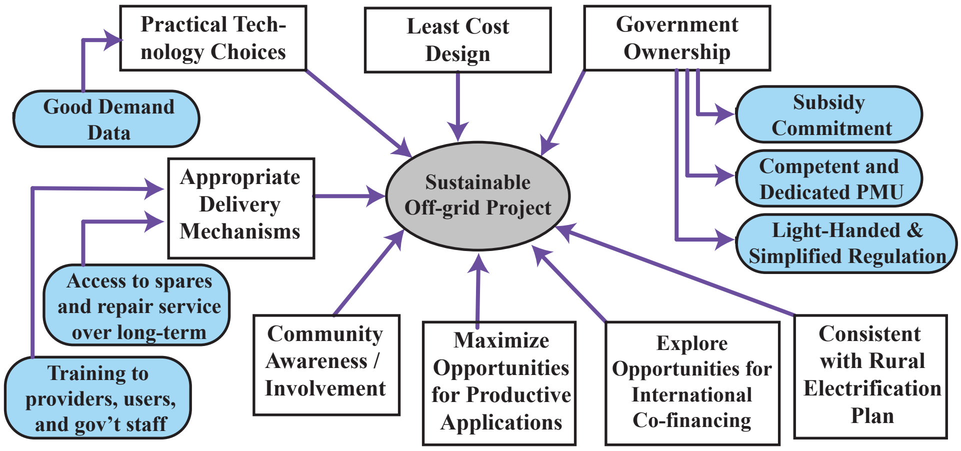

Figure 2.1: World Bank Sustainability Design Map (Re-rendered by author from: [8])

is cited most often in other texts. The elements can be classified under sustainability factors (i.e. technical, social, economic, organisational, and environmental). The design map provides guidance for high-level decisions such as technology selection and scaling considerations (concentrated mini-grid or distributed solution), much like in the first section. Unfortunately the issues noted previously with generalised guidance are not resolved in this section.

One challenge is that the low level of detail of the success factors prohibits them from being applied more generally. For example, for *private-sector participation in a project*, the "simplest delivery mechanism or business model (or mix thereof) commensurate with local realities should be applied" [8, p. 20]. Sensitivity of the design is needed to respond to "capabilities of the service providers, adequately address their risks, provide technical assistance" [8, p. 20] to list a few. All of these suggestions are clearly valid but subject to significant subjectivity should they be followed – both in terms of scope and method.

A second challenge is that the linkages between each success factor are not defined. Neither the map or text discusses the connections between, for example, practical technology choices, maximising opportunities for productive applications, appropriate delivery mechanisms, community awareness or consistency with the rural electrification plan. The mix and emphasis of each is of critical importance to a given project's success.

Instead they are shown as a dimensionless unit and simply relating, somehow, to a black box representing sustainability.

Third, and related to the second challenge, is how one would handle deficiencies in a success factor or plausible variations of the design. It is lacking sensitivities or some means to handle sensitivities. If projects waited to be "consistent with rural electrification plans" [8, p. 19] then lack of an off-grid component to the plan would invalidate the majority of installed projects. Equally, if an opportunity to maximize productive applications was not a major part of a project, does it necessitate failure?

Fourth, there is almost no intention to address sustainability success factors which arise outside of the design stage of a project. The closest attempt is when the toolkit recommends long-term support for the supply of spare parts and qualified repair services. However, the recommendation is primarily focused on establishing that such a service exists as a requirement to the design stage. Provision of training is also discussed, but again, the toolkit's recommendation is restricted to training during the design stage. Though the document is open with its intention, *project design guidance*, the negligible mention of operational issues leaves open many potential questions which could have a critical impact on project success. Perhaps the top question would be on the guidance as a result of a major change in the design stage expectation of projects, for example the unexpected reduction in community involvement? One exception to this from the first section is the Nicaragua case study, which *could have* been cited as guidance in this project stage as it involved responding to the observed situation (low ability to pay) with a relevant response (local economic development activities) – instead it is unutilised.

Toolkit Conclusions

The World Bank technical note was reviewed in this section with a focus on its ability to capture and provide guidance for off-grid electrification projects. The document contains a vast amount of guidance, with each individual item unequivocally relevant to project sustainability. However, this critical review found several weaknesses which limit its overall value towards project sustainability:

- Specific references to projects are used as anecdotes and do not stand in for generalised guidance.
- Generalised guidance is insufficiently coordinated to be practically useful and in some cases inconsistent with the presented specific references. The guidelines avoid prescription by design instead suggest a case by case application.
- A low level of detail of the success factors prohibits them from being applied more generally. This leaves significant subjectivity on how should they be followed – both in terms of scope and method.
- The linkages between each success factor are not defined – though the mix and emphasis of each is of critical importance to a given project's success
- Sensitivities around application of success factors leave the impact of many potential variations on a design unclear. A deficiency of even one factor has an unknown sustainability impact.
- Operational stage sustainability guidance is largely unaddressed.

With respect to project sustainability, the totality of guidance in the World Bank Note is disappointing. Its stated purpose of avoiding hard prescriptions has dominated its guidance and in doing so, sidestepped much of the critical detail practitioners and researchers need for extending the results. Instead, the guidance traverses topic to topic while offering pared down generalities, disconnected anecdotes, and avoidance of sensitivities. A detailed analysis of these ambiguities and nuances is needed.

While it may be true that supporting case studies for each project has detailed analysis, the lost opportunity here is that the toolkit stopped short of fully synthesising the results such that they were accessible by future practitioners. In the WB toolkit, sustainability resides in a black box, with issues that affect project sustainability recognised but only nebulously connected to the project's life-cycle. In order to learn from past projects and systematically improve the chances of future projects, it must be duly investigated. This thesis addresses the same black box that the World Bank Toolkit effort fell short in their analysis.

How should sustainability guidance in the World Bank toolkit be viewed of in light of this conclusion? This guidance should be carefully reviewed as there is ample room for interpretation. A model which does not fully fit the World Bank vision must evaluated *ad-hoc* or with some other (external) expertise. At the same time, for a prospective project which does fit the model, how will it manifest in the local context? Each topic and item of guidance presented has wisdom, but there is a significant burden for the reader when drawing and defining their connections.

2.2.2 AFREA Photovoltaics for Community Service Facilities Toolkit

Another resource designed specifically for sustainability guidance in the establishment of community PV projects was produced by Africa Renewable Energy Access Program (AFREA) in association with the World Bank and ESMAP [9]. The guidance points out that "[t]he key aim should be sustainability, which at the minimum is the reliable, cost-effective operation of a system over its design lifetime" [9, p.5]. It organizes a phased approach which includes rapid pre-assessment, implementation planning, install, and long-term ongoing operation. The guidance provides very detailed suggestions throughout this process based on the authors' experience in four developing countries (Zambia, Mozambique, Philippines, and Tanzania). Although the emphasis of the document is dedicated to community solar projects, the guidance around non-technical and development aspects is widely relevant to other projects.

A case study in Zambia is referenced in order to describe the sustainability gaps present. In this case it included poor choice of technology, failing to account for future grid extension plans, procurement and implementation delays, poor standards of system design and installation, non-transparent design process, wrongly sized systems (both over- and under-designed), under-defined system ownership, no system performance tracking and supervision, user and operator skill levels with renewables, low community involvement, adverse environmental hazards left un-addressed, and instances of theft and vandalism. The attention to potential failure points is strongly emphasised throughout the toolkit, both with specific examples and generalised guidance [9, p.7].

The AFREA toolkit's guidance towards specific sustainability pitfalls, sustainability focus throughout the project life-cycle, and practical focus make it an excellent reference source for project development steps. Sustainability issues are addressed during all

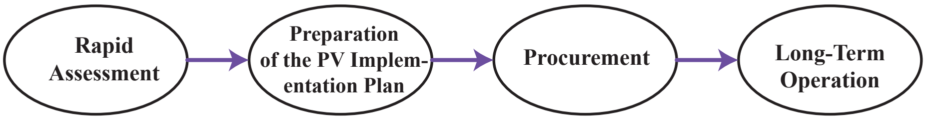

Figure 2.2: AFREA Project Development Stages (Adapted by author from [9])

stages of the project life-cycle: rapid assessment, preparation, procurement, and long-term operation of the project (see Figure 2.2). For example, during the system design stage, the design margins (arbitrary excess sizing) discusses the reliability and cost trade-off of the project [9, p.25]. Long-term sustainability planning includes considerations for technical operation through the establishment of maintenance contract based on established performance metrics and non-technical issues. Non-technical issues that are addressed include provision of training and skill maintenance, and a continued role for community involvement in the project.

The AFREA toolkit is comprehensive and has few weaknesses from a sustainability standpoint. However, the handling of indicators for performance monitoring provides only limited detail for implementation. Although it states "system performance and maintenance should be carefully recorded… offer the promise of rapid responses to problems and sound monitoring, contributing to reductions in operating costs, improved reliability, and longer-term sustainability", the selection of indicators and relationship between these indicators, decision-making and results are not established [9, p.50].

As a result, the relevance of the toolkit in guiding long-term sustainability rests primarily on its design guidance. After the design of the system using the toolkit, there is no further guidance on the operational challenges which arise. This leaves a critical question unanswered: how does the operator respond to the performance indicators and measure the results of subsequent changes they make?

Another weakness is lack of systematic project experiences: "there is no comprehensive compilation of projects with PV systems in community facilities, nor any randomized testing…" [9, p.20]. Futhermore, the authors identify the problem of "paucity of relevant time series data on the comparative operation of PV systems installed using various technical and institutional approaches" [9, p.5]. This issue is related to the prior weakness and points to the need for attention to data management and analysis post-design.

2.2.3 EUEI Mini-Grid Policy toolkit

The EUEI Mini-Grid Policy Toolkit [6] is a high profile toolkit published by a partnership of Renewable Energy Policy Network for the 21st Century (REN21), Alliance for Rural Electrification (ARE), EU Energy Initiative (EUEI PDF), and Africa-EU Renewable Energy Cooperation Programme (RECP) in 2014 and covers topics around the design, implementation, and policy frameworks of mini-grids in developing countries. Although it is targeted towards African policy makers, it introduces many sustainability concepts for mini-grids. Policy prescriptions for design and potential scale-up of mini-grids in Africa cannot be separated from the sustainability issues underlying them.

Sustainability issues that are discussed include: low data availability, tariff setting that misses key elements of the cost structure, inflexible tariffs, no spare parts, general mismanagement to plan for operations and maintenance, lack of continuation following the donor-cycle, licensing red tape, low skills for managers, operators, technicians, insufficient policy and regulatory frameworks. Additionally, a series of macro-level risks are presented including political risks[4], social risks[5] , economic risks[6], and others [6, p.68-70].

The EUEI toolkit summarises guidance from a selection of literature sources and summaries of international experiences[7]. Areas of coverage include operational/ownership models, overview of typical economic conditions, tariff structures, financial considerations, overview of stakeholders (consumers types, operators/utilities, financiers), and extensive policy and regulatory guidance. As the document is aimed primarily towards African policy makers looking to scale up mini-grid roll-out, only limited attention is paid to exploring the past sustainability issues and connecting the prescriptions to the

[4] Such as regime/government instability, policy changes, industrial action, taxation or import duty changes, legal, and regulatory changes such as obtaining permits, energy regulation risk, and health and safety.

[5] Risks to fauna/flora, pollution, waste, criminality, non-acceptance

[6] Including lack of finance availability, interest rate risk, credit risk, currency risks

[7] See [6, p.25]. This includes Kenya, Mali, Namibia, Senegal, Tanzania, Zimbabwe, Brazil, China, India, Nepal, and Philippines.

	Utility Model 1	Hybrid Model 2	Private Model 3a (unregulated)	Private Model 3b (regulated)	Community Model 4
Cons	› Not the core business; › Unsuited company structure for smaller projects; › Strain on limited budget; › Political interference; › Possibly corruption in procurement;	› Complex management, feasibility of models depend on regional/ local context/ structures; › Non-fulfilment of contracts due to conflicts between business partners; › Insolvency of one partner (either SPD or SPP) puts full operator model at risk	› No financial support from public obtainable; › Grid interconnec-tion challenging / impossible; › Changes in regulation and fixed tariffs can reduce profitability; › Conflicts with customers due to monopoly; › Insufficient quality and safety risks of service can occur if it is not supervised, which can contribute to a bad image of mini-grids	› Reliable regulation needed, dependency on lengthy approval procedures; › Debt financing needed for scaling up; › Vulnerable to changes in regulation, fixed tariffs, conflict with customers; › High transaction costs; › Potential risk: grid interconnections	› Insufficient local human (technical and management) capacity; › Often unclear ownership structure; › Usually high grants needed; › Tariffs not covering operation and maintenance (O&M) and reinvest-ment costs; › Corruption risk due to overlapping of management and social and family connections

Figure 2.3: EUEI Toolkit Business Model Cons (Sustainability issues), (Re-rendered by author from [6, p.37])

symptoms, instead it favours highlighting of successful models.

The toolkit handles sustainability generally with only several explicit discussions around particular sustainability issues. These issues are most readily framed as drawbacks for potential business models as shown in the Figure 2.3 (Re-rendered from [6, p.37]). Although these issues have been proposed, how they occur, nuances in their manifestation, and how they can be addressed are not fully addressed in the document. This critique can be repeated for the risks presented earlier [6, p.68-70]. Again the emphasis on supporting policy making rather than implementation or project developers can partly explain this lack of attention.

Many of the presented sustainability issues receive only a cursory mention throughout the supportive text. For example, the toolkit identifies low skills (see community model 4 in Figure 2.3) as an issue with community models [6, p.37] and offers the high-level guidance that capacity building should be included in technical assistance and a training curricula developed [6, p.98-99]. Absent, for example, is any guidance on levels of specific skills and their potential impact on project sustainability – they simply must exist. Unlike other toolkits, there are no indicators offered that could be used to measure the level of skills and connect them to other sustainability issues.

Several other examples lack sufficient depth. For example – lack of tariff flexibility, is addressed indirectly by presenting the tariff options which do provide flexibility (pay as you go, demand based tariff) [6, p.49-50]. The problem of theft and distribution losses is solved by "involving local communities from the start" [6, p.58] and by leaving "some decision-making power to the community through discussions (sometimes also negotiations) on eye level between the mini-grid operator and community representatives" [6, p.58].

It is explained that customer conflicts arising from a monopolistic concession for a mini-grid occur when customers have no recourse to complaints and inherently have a weak position due to a design of the concession [6, p.93]. Although more thoroughly explained than other issues, it still does not have sufficient detail as to how to measure and respond to such conflicts should they occur. Further, there is no guidance on how it actually affects project sustainability should the issue be unaddressed or even occur. Other issues, such as community acceptance and scarcity of data for technical/economic system design, receive only light coverage. Impact, considerations, and mitigation approaches for the risk of non-acceptance by local communities, another issue, are not discussed.

EUEI Toolkit Conclusions

For policy makers, the EUEI toolkit takes a view that sustainability is mostly a foregone conclusion. Although the issues and risks are acknowledged, they are not a pressing concern. Risks and business model concerns exist but are binary in nature and the toolkit has little guidance on handling them when they occur. Instead, the EUEI toolkit quite clearly centres policy design as the process which ensures sustainable projects [6, p.101-113]:

> "Today's main barriers for mini-grid deployment are not related to techno-

logy, but to economic, financial, regulatory aspects as well as institutional and human capacity. Past experiences have revealed challenges with the sustainable operation of mini-grids. However, examples from both Africa as well as from other regions have shown that these problems can be overcome, in particular through business driven approaches" [6, p.15].

For secondary audiences including project developers, practitioners, and researchers, the following weaknesses limit the value of the toolkit:

- Insufficient support for handling sustainability issues outside of regulatory framework development.
- No measures or indicators that could be used to track project sustainability.
- Unexplained definition of the interrelationships between issues.
- Evidence base is limited and disconnected from toolkit.
- Sensitivities around application of success factors leave the impact of many potential variations on a design unclear. A deficiency of even one factor has an unknown sustainability impact.
- Operational stage sustainability guidance is largely unaddressed.

2.2.4 GIZ Toolkit

GIZ's series of three handbooks published between 2014 - 2016 [86–88] constitute a toolkit aimed at primarily solar-PV based mini-grid design development. The content focuses on three main areas: site selection, licensing concerns, and system sizing aspects. The toolkit's evidence base is drawn almost entirely from GIZ's experience in Kenya. In 2013, an evaluation of 14 sites was completed for projects involved in the $720 million Scaling-Up Renewable Energy Programme (SREP) for Mini-grids [89] and funded by the Climate Investment Fund.

At a high-level, the toolkit offers only implicit guidance on sustainability. By preparation of the documents and templates, following the project design recommendations, and site selection method, sustainability is assumed to be higher. Major limitations include identification of specific sustainability issues, recognition of sustainability gaps in the sector, and use of precise metrics to capture sustainability.

The **site selection section** [86] concerns five main categories of site selection: physical geographical location, identifying productive uses of energy, determination of willingness/ability to pay, demand forecasting, and security issues. The site selection methodology evaluates locations versus a total of 19 considerations organised under the categories. The scores and weighting are not specific and can be revised for each site selection. Metrics include such items as *Payment for Services*, *Distance to Power Sources*, *Payment for Services* and others.

Although the categories and metrics are relevant to sustainability, the scoring approach is problematic – limiting reproducibility. As an example, scores on *Payment for Services* can be selected from 1 (Low), 3 (Average), and 5 (High). There are no explanations on exactly what the score means or guidance on relativity to other projects, making them subjective. Further, the same metric also stands in for both ability to pay *and* willingness to pay, presumably 2 sub-metrics of the overall score which again have no guidance on how to weight these against each other. The definitions of metrics, for example, *ability to pay* includes vague descriptions like "prevailing economic activities" and "disposable income". These methodological issues are further compounded as there is no guidance on how to weight the high-level categorical metrics on their sustainability relevance. The connection to sustainability of the categories is never established despite the claim at the onset that site selection has a "heavy impact, among other factors, on attracting both public and private investments and the overall sustainability of system" [86, p.5]. Although the site selection section introduces the use of metrics for evaluating a project's sustainability, its framework is weak in terms of clarity, relevance to sustainability, precision, and reproducibility.

The **licensing section** [87] of the toolkit concerns the regulatory requirements of a mini-grid and other institutional arrangements needed for sustainability. The section captures learning from the process of licensing a mini-grid in the town of Talek, Kenya. The relevant authorities that are involved in licensing, required documentation, and outline of the procedures are described. While most of the section is of practical importance, sustainability issues are only implied by the requirement to complete of specific documents – there is no discussion of specific sustainability requirements. Licensing requires a financial model, an environmental impact assessment, and "project report by a competent engineer" [87, p.12], but these resources are not evaluated to forecast sustainability. As a result, this section is of primary importance to the project design stage and does not directly concern sustainability.

The **sizing section** [88] concerns the technical system sizing of a mini-grid. The document covers current and aspirational demand estimation, input data needed for a techno-economic system design software (HOMER), demand management options, and an overview of the software tools. The practical design steps are logical and necessary to the design a sustainable project, but are not sufficient. Primarily, the toolkit guidance seeks to deepen the understanding of demand forecasting in the context– how to arrive at an effective demand from a variety of data sources such as surveys, how to incorporate willingness to pay into demand forecasting, types of system design software, and introducing tariff options. The section makes it clear that sustainability is at stake: "When sizing a financeable and long-term viable mini-grid, future growth in the effective electricity demand has to be considered" [88, p.30] and "Defining an acceptable tariff structure for the residents of the rural community is crucial for the financial viability of the project" [88, p.40].

Practical guidelines are provided for PV array sizing, battery sizing, limited inverter specifications, battery operation, and others, but the bulk of design decisions are accomplished through a list of recommended software packages[8]. In combination with the considerations of demand forecasting, tariff design, sizing rules-of-thumb, and software resources the toolkit covers the techno-economic considerations relatively well. This section comes closest to tying together a sustainability model, but falls short in its treatment of other factors besides technical or economic and only minimally attempts to address specific sustainability considerations. There is no discussion around operational issues, development of performance indicators, or the interaction between sustainability factors.

[8]Including: Mini-grid builder, Homer Pro, and SMA Sunny Design. See Section 4.2.4 for a more extensive discussion of how such software packages overlap sustainability considerations in the context of off-grid electricity access projects.

In summary, GIZ's toolkit treats sustainability implicitly through the outlining of steps to site, license, and design a mini-grid. While its emphasis on practical guidance for design is apparent, the main gaps were:

- Insufficient recognition of sustainability gaps that the toolkit seeks to address. The guidance implies that it addresses sustainability, but only indirectly.
- Poorly designed indicators lack reproducibility and are applied only to project siting.
- Unexplained definition of the interrelationships between issues.
- Evidence base is extremely limited to the Kenyan experience.
- Operational stage sustainability guidance is largely unaddressed.

2.2.5 Discussion of Toolkit Gaps

In this section, four prominent toolkits were reviewed to determine how they provided guidance towards sustainability issues for off-grid projects in developing countries. Figure 2.4 illustrates the types gaps that were found in the scores the toolkits. Each toolkit is scored against 7 factors and discussed further below (emphasised with bold). Overall, the AFREA toolkit tended to have the highest scores and offers the strongest guidance for project sustainability. There were notable weak points particularly around the guidance for the use of indicators within project that could be used to generate robust evidence.

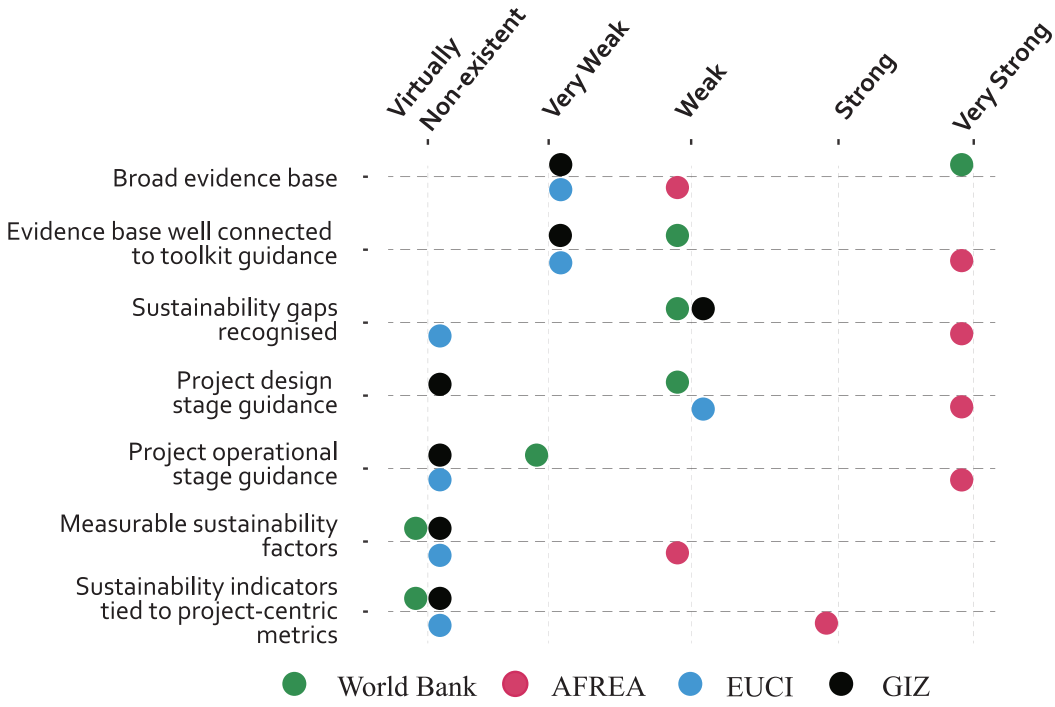

Figure 2.4: Comparison of Toolkit Gaps

A **broad evidence base** to draw from is the basis of toolkit guidance. The best documented was the World Bank toolkit, which captured learning from many programmes globally and had supportive project documentation. However, most toolkits tended to have evidence sourced from only a handful of country experiences. Commonly, the successful case studies are referenced versus those that had sustainability challenges.

Connecting the evidence base to the guidance demonstrates that learning from past projects is effectively translated into forward looking recommendations. With the exception of the AFREA toolkit, guidance virtually ignored the evidence base and was only implicitly connected to actual data.

Though it could be assumed that **sustainability gaps would be recognised** by the toolkits created in part to address sustainability, this was not the case. Instead the actual sustainability issues tended to be glossed over, typically by focusing on the positive aspects of a case study rather than providing explanation why particular guidance was important. Chapter 3 finds that sustainability issues continue to hamper projects, suggesting that further research is needed to be better understand the interrelated factors. While sustainability remains in question, identification of the actual issues that are being addressed will support more purposeful learning.

Guidance tended to be more relevant to a project's **design stage** versus **operational stage** amongst the toolkits. This review finds that there was over-reliance on the design of a project. The dependence on design produces a premise with the guidance of 'sustainability-by-design'. It can be granted that design decisions are critical to sustainability and serve to create operational limitations that can made later on, especially related to technology adjustments, but equally it would be unfair to portray the project as set in stone. With respect to operational stages guidance only the AFREA toolkit provided detailed guidance on post-installation sustainability challenges and decisions making support.

Measurable sustainability factors are needed to quantify the levels of project sustainability. With the exception of the AFREA toolkit, no other toolkit specified how sustainability was measured in explicit terms. Furthermore, no toolkit discussed how to connect the indicators to sustainability factors or tracked them throughout the project. As a result there was no guidance on how to evaluate the sustainability of projects using indicators. This leaves the interventions or purposeful innovations taken in a project difficult to evaluate. In some cases, the indicators themselves are overly broad, for example when in the EUEI toolkit, defining the community involvement factor, it is never clarified whether community ownership of a project, community contributions, early or continued involvement by the community (etc.), or all, represent this factor [6, p.60]. The GIZ toolkit had large gaps where critical factors, cited in other toolkits, were hardly mentioned (community involvement, supply chain/replacement parts, training/skills, etc.). The AFREA toolkit, which most readily addressed operational guidance, still limited this to technical maintenance – overlooking any indicators for other sustainability issues such as load creep, theft, and vandalism [9, p.52]. Where it had indicators, the AFREA toolkit **tied these to project-centric metrics**, which are needed in order to evaluate whether a given project is sustainable.

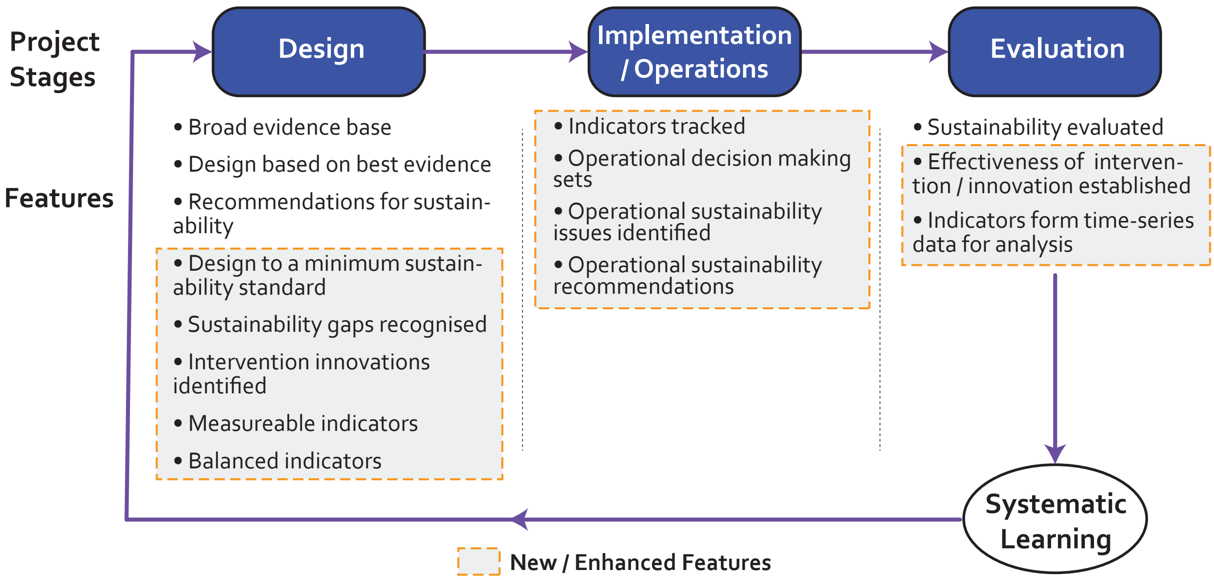

Figure 2.5: Proposed “Repository of Sustainability Knowledge” Toolkit Format

2.2.6 Proposed Toolkit to Improve Sustainability

In response to the weaknesses identified, several enhancements are recommended for toolkits that would improve their credibility and relevance for practitioners implementing off-grid projects in developing countries. Recommendations are summarised first followed by a more in-depth discussion.

First, the evidence base from which sustainability guidance is given should be better connected in the toolkits. Guidance based on single case studies lose relevance outside that specific context – a broad evidence base is required (as per the AFREA and World bank toolkits). Moreover, recognition is needed within the toolkit on the gaps in the literature that might affect a given project's sustainability prospects. This will help ensure design and operational decisions are not made on false assumptions and, at the same time, point to areas where more learning is needed.

Second, defining sustainability factors (and sub-factors) should include measurable scales. Without this, sustainability becomes subjective, difficult to track and to establish learning. All the toolkits agree in the importance of measurement of sustainability factors, but the guidance is inconsistent. Building on the AFREA toolkit for example, one sustainability issue identified is “Misuse, poor maintenance. . . ” [9, p.7] and a maintenance regime activities based on measurable conditions: "Read and record dial indicators on charge controllers. . . check battery levels. . . " [9, p.51]. All the toolkits insist on financial sustainability but none actually specify the key indicators needed to prove this: revenues and expenditures.

Third, toolkits could address an over-reliance on sustainability-by-design by providing guidance on how to handle sustainability issues over other stages of the project. The biggest gap is during post-installation operational stage. The toolkits currently provide only a descriptive overview of the project life-cycle. It is suggested that toolkits should instead seek to answer the key question of: if the project design constraints have been set, what types of sustainability issues arise and what recommendations are possible to bolster sustainability of the project? Additionally, since learning about sustainability is still underway, a common measurement is justified to help make learning more systematic.

Although this discussion has been critical of toolkits, the intention is constructive. The proposed enhancements envision the role of toolkit as a repository of knowledge that is justified and provides evidence for sustainability prescriptions, relevant through all stages of the project, and implementing a common framework for evaluation that allows for systematic learning. A general format for the proposed toolkit is shown in Figure 2.5 and described in terms of critical features present at each project stage as shown in the blue boxes. New features are highlighted in orange while existing design-focused toolkit features are listed alongside.

Design Stage Enhancements

New features in this framework are linked to the enhancement suggestions. In the design stage, a minimum sustainability standard should be linked to each sustainability factor (or sub-factors). Minimum standards are needed when there are absolute requirements for a sustainability factor (i.e. sizing requirement, component quality standard, minimum skill/tooling requirements). Additionally, minimum standards are useful in any case because they focus the attention of the recommendations. Setting a minimum level of reliability of service over a 20-year project life-cycle is critical for technical system design, maintenance plans, and component replacement strategies.

Addressing sustainability gaps by establishing known project pitfalls and challenges which do not have immediate solutions is critical towards signalling future research needs. In this Section it was established that toolkits tend to favour analysing positive project experiences rather than failures. Experiences with project fail states should therefore be examined with much more rigour. The literature review completed in Chapter 3 finds that the discussions of sustainability issues in project reports were often concentrated in issues within specific categories, suggesting a varied understanding by practitioners. Toolkits should therefore intentionally identify known sustainability issues, and emerging issues to support the active learning process in this area.

As the evidence suggests that project sustainability issues are an ongoing challenge (see Chapter 3), innovations (if any) need to be identified for each intervention. Sources of innovations can vary: successes spotted in pilot projects, mitigation measures for projects which have faced steeper challenges, or inspiration from other sources. Similarly they can take different forms: social support arrangements, business or economic model designs, use of specific technology or technical solution, or emphasis on various end-uses – to name a few. Attribution of the innovation's effect on project sustainability is critical and made all the more challenging given the information sparsity.

Indicators, already present in many projects but implemented inconsistently, need refinement and justification to make them more relevant for sustainability issues. In Section 2.3 indicator literature is analysed and best practices are drawn out for implementing indicators. In short, for indicators to be tracked and later compared, it is important that they are practically measurable and balanced to cover all sustainability aspects and against each other.

Finally, recommendations should be laid out for each project stage, thereby offering an alternative to sustainability-by-design. Toolkits that are heavily oriented towards recommendations in the design stage neglect other stages of the project life-cycle. This weakness draws attention away from beneficial advice that could be made to improve project outcomes after the initial design is completed. Historically, international development projects, where much of the learning in the sector has thus far been accumulated, are far better at starting projects then seeing them through as the years go on. The priority of design-based recommendations is thus not surprising. However, it is virtually unthinkable to imagine a business in any industry to regularly overlook decision-making in the operational space.

Implementation Stage Enhancements

Implementation stage enhancements apply to sustainability considerations that occur after a project has been commissioned and normal operations are underway.

First, sustainability indicators are needed for the basis of all decision-making and evaluations later on. As discussed, implemented indicators need to be linked to the sustainability of the project itself and periodically reviewed to ensure their relevance. During the implementation stage, normal operation of the project is underway, and the project operators are actively managing the project. Idiosyncrasies in which some indicators are not relevant to a specific project aside, a standard set of indicators can be tracked and used for active decision-making. It is important to differentiate the use of these indicators at this stage versus the evaluation stage. While operating a project, indicators are akin to Key Performance Indicators (KPIs) that are widely used in project management literature. According to Toor and Ogulana [90] the 'iron triangle' (on-time, under-budget, according to specification) KPIs which are the most widely used are now supplemented with a variety of measures which are most appropriate for the application. Horkoff et al. demonstrate KPI and indicator reasoning approaches that are used in a general business sense [91]. In the implementation stage of an off-grid electrification project, KPI methodology is clearly valid.

Second, inclusion of an empirically motivated decision set consisting of how project operators make operational decisions is needed. Generally, operational decision-making aims to adjust available operational parameters to optimise project performance. While a host of operational states may be experienced by the operator, it is important to know under what circumstances any changes to operational approach occur. A measurable indicator(/s), set of decision rules, and definition of underlying mechanic(/s) can be used model operational decisions (See Chapter 4 for an implementation of this). Practically, the toolkit could contain default decision-making assumptions based on best practices of the known project base and tailored, where appropriate, to local circumstances.

Third, the toolkit should document sustainability issues which are known and occur within the operational stage in addition to design issues. Some sustainability issues overlap stages but can have different strategies to address the issue. For example a low availability of supply modelled in the design stage may suggest simply designing a larger system. In the implementation stage, the same issue may have several solutions - lowering expectations with customers, shifting or removing sources of unprofitable energy uses, investing to expand the system, or investing to improve operational efficiencies, to name a few. Other sustainability issues are mostly operational issues: staff skill management, staff retention, marketing and sales activities, and ensuring fair access to project benefits. Even the best project design planning will fail to identify all situations which occur and will find incorrect assumptions. Operators must be able to effectively respond to design stage failures, gaps, and incorrect assumptions, or shortly: adapt.

Evaluation Stage Enhancements

The evaluation stage of a project play an important role in accumulating systematic learning that can be re-incorporated into iterations of the toolkit and future projects. First, as a result of a consistent set of indicators that are tracked over the life-cycle of a project, time-series data can be used to conduct the analysis. Higher granularity of data is preferred but is often a trade-off between cost/effort and value. However, any improvement beyond a baseline/end line method, that captures only two points in time, that is typically employed by development practitioners is a critical clue to the sustainability evaluations.

Second, sustainability evaluation should strive to make a judgment on the current and future expected sustainability and also be used to compare the effectiveness of various interventions and innovations that are tested. Without consistent, strictly relevant to off-grid development projects, and sufficiently granular set of indicators, analysis of innovations are subject to many confounding factors and researcher biases.

Overemphasis on particular hot button issues for a given discipline, be it economic, technical, or social, can weaken the analysis. Additionally, unintentionally leaving gaps in the indicator coverage or inserting irrelevant indicators, but which might be of general interest to the development progress of a project, confuse the analysis and can make the conclusions incomparable.

The enhanced view of the evaluation stage described in Figure 2.5 is designed for comparability of evidence so systematic learning can be produced and strong arguments can be made on the effectiveness of innovations made. A consistent set of indicators assist with systematic research that can be regularly incorporated into subsequent versions of toolkits. As described in this section, current toolkits are based, at best, on diverse data spread over a range of projects or, at worst, a limited set of projects with indicators that are intrinsically related to sustainability. If one accepts that learning how to ensure sustainability of such projects is important, than the diversity of data and haphazard approach to synthesising it is actually a problem. In contrast, restricting the indicators used to a curated set and even defining the relevant analysis method to utilise these indicators, will more easily produce systematic learning.

2.2.7 Conclusions

The section has presented prominent toolkits and identified current gaps that reduce their ability to implement sustainability guidance. The problems found include lack of an evidence base (supporting sustainability guidance), inconsistent specification of sustainability factors, low guidance around the interrelationship of sustainability factors, and an over-reliance on sustainability-by-design approach. A new framework for toolkit design addresses was proposed to address these gaps. Notable changes to the design include incorporating measurable indicators that are linked to sustainability factors and implemented throughout all project stages, the addition of operational decision-making and operational sustainability into the guidance space of toolkits, and involving evaluation explicitly in the process so that more systematic learning can be generated (based on a time-series of indicators). In total, the framework envisions toolkits' scope extended to become a repository of sustainability knowledge guiding project developers throughout all the project stages and driven by a systematic learning process.

2.3 Sustainability Evaluations with Indicators

A sustainability evaluation generally consists of scoring a project against a set of indicators that represent sustainability dimensions. Such evaluations are understandably an important part of developing learning around what aspects of a given project contribute or detract from its sustainability. The choice of indicators, how they are captured and quantified, and how they are combined into a judgement are all methodological decisions that put boundaries on the conclusions that are made on a project's sustainability.

A substantial body of literature now exists for indicator frameworks that are used to measure or estimate sustainability of off-grid electricity access projects [25, 33, 70, 71, 75–81]. This section critically analyses the origins of the prominent frameworks and traces their development to recent works that are applied to off-grid programmes and projects. Following the review, gaps are identified and revised criteria are proposed for designing and selecting indicators.

This thesis makes a distinction between *outcome-centric* indicators versus *project-centric* indicators, as per the definition of sustainability established in Section 2.1. Whilst the definition covered the historical origins of sustainability with a wide lens, which included indicator frameworks, this section discusses the content of those indicators with added detail. It is argued that indicator frameworks remain linked to the sustainable development origins (outcome-centric), in essence, serving to validate whether a given project is able to achieve a specific outcomes. Some aspects of indicator frameworks have evolved pragmatically over time towards more project-centric indicators.

Key Insights from Section

- Indicators are typically used in the evaluation of project sustainability and hence are a critical process step towards learning.

- Sustainability indicators in the literature are rooted in the outcome-centric objectives stemming from the United Nations. This legacy remains prevalent even with modern indicator sets.
- Outcome-centric indicators do not have closely coupled connection to the sustainability context of a project. As a result, evaluations and learning which utilise these indicators can assess project outcomes, but not sustainability. Three critiques are offered that limit the validity of outcome-centric indicators: [1] indicators that are relevant to the global context but not the local context, [2] indicators that are select to track extrinsic data associated with development indicators, and [3] indicators that target a development outcome with no clear feedback to a project's operations.
- Recent literature has interspersed project-centric indicators which represent a methodological advancement.
- A novel criteria for indicator inclusion is proposed. This consolidates the criteria proposed in the literature and is extended to be project-centric.

2.3.1 Origins of Outcome-centric Indicators

Prominent indicator frameworks for sustainability analyses of off-grid electricity access projects (namely [10, 16]) can be traced to major international efforts to measure and guide progress towards sustainable development. Consequently, it has become standard to conduct sustainability studies for these projects using the language of sustainable development, in particular, the characterising sustainability as three pillars composed of: social, economic, and environmental considerations [92]. However, this may be due more to the popularisation of the language through the UN rather than a result of theoretical rigour. The term 'sustainable development' is purposely ambiguous so that competing conceptualisations can co-exist and coalesce around a single vision [93, 94]. This matters to individual projects since the legacy of the indicator frameworks persists. The ambiguity towards the definition of sustainability, as a result of the this legacy, confuses sustainability planning in all stages of a project. Practically-speaking, the inclusion of outcome-centric indicators reduces the emphasis on project-centric indicators which could be used more directly to guide sustainability decision-making as well as support robust learning.

The United Nations (UN) Indicators of Sustainable Development [74] were first published in 1995 – 1996 and were designed for countries for "developing new indicators to measure progress towards nationally defined goals for sustainable development" [74, p.1]. These followed from the Rio Declaration in 1992 that laid out 27 principles, for example: establishing the need to protect the environment, cooperative action to address poverty and pollution among others [95]. Both built upon the 1987 Brundtland Report which defined the well-known definition of sustainable development: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." [72].

The current edition of the UN indicators was published in 2007, and has been updated to reflect the Millennium Development Goals (MDGs) which aimed to "to address extreme poverty in its many dimensions - income poverty, hunger, disease, lack of adequate shelter, and exclusion – while promoting education, gender equality, and environmental sustainability" [14]. In 2015 the UN adopted the Sustainable Development Goals (SDGs) that expanded the goal count and reinforced the development agenda established by the MDGs [96–98]. A selection of UN sustainable development indicators is shown in Table 2.2. The collection of indicators clarifies the UN's conceptualisation of sustainability – one that is rooted in specific development outcomes.

Table 2.2: Sample UN Sustainable Development Indicators (Selected from [14])

Category	**Sample Indicators**
Poverty	Proportion of pop. living below national poverty line, Ratio of share in national income of highest to lowest quintile, share of households without electricity or other modern energy services, proportion of urban pop. living in slums
Governance	Perc. of pop. having paid bribes., No. of intentional homicides per 100,000/pop.
Health	Under-five mortality rate, life expectancy at birth, Perc. of pop. with access to primary health care facilities, prevalence of tobacco use, nutritional status of children
Education	Net enrolment rate in primary edu., adult literacy rate
Demographics	pop. growth rate, total fertility rate, dependency ratio
Land	Land affected by desertification, arable and permanent cropland area, proportion of land area covered by forests
Atmosphere	Carbon dioxide emissions, consumption of ozone depleting substances, ambient concentration of air pollutants in urban areas
Economic Development and GDP/capita	debt to GNI ratio, share of women in wage employment in the non-agricultural sector, internet users per 100/pop.
Global economic partnership	Current account deficit as perc. of GDP, Net Official Development Assistance (ODA) given or received as a perc. of GNI
Consumption and production patterns	Material intensity of the economy, annual energy consumption, total, and by main user category, generation of hazardous waste, modal split of passenger transportation

Alongside the development of more general sustainable development indicators, the International Atomic Energy Agency (IAEA) developed a specific set of indicators for energy issues "consonant with the larger effort on Indicators of Sustainable Development" [15]. With the IAEA indicators, the sustainability pillars classification (social, economic and environmental) has become the norm for energy related initiatives. The IAEA indicators (see Table 2.3) clearly have a priority on energy issues and seek to link these to development outcomes. While the UN and IAEA indicators are highlighted in this research, it is important to note they are not alone. A healthy number of indicator frameworks, each with varying definitions of what 'development' means exactly, have been proposed by various entities [99].

Table 2.3: Sample of IAEA Indicators (Selected from [15])

Category	**Indicators**
Economic	Energy use per capita, efficiency of energy conversion, household energy intensities, reserves to production transport energy intensity, fuel shares in energy and electricity, renewable energy share, net energy import dependency
Environment	GHG emissions, air pollutant emissions from energy systems, contaminant discharges from liquid effluents from energy systems, soil area acidification, rate of deforestation attributed to energy use, ratio of solid waste properly disposed of vs. total generated
Social	Share of households without electricity, Share of household income spent on fuel and electricity, household energy use for each income group, Accident fatalities per energy produced

Though the emergence of sustainable development indicators have been prominent, their usage have come with criticisms. Purvis argued that there remains a lack of a common theoretical basis in their development [92]. Kidd has identified at least six different origins of the use of 'sustainability', each with competing concepts but sharing the term for their own purposes [100]. The ambiguous conceptualisation of the three pillars is necessary for competing views – as is reflected by omission of potential targets and lack of commitments to targets that have emerged as the SDGs have come to the forefront [98]. Kates et al. posited that the 'creative ambiguity' of the alternative definitions allow for programmes at different scale and purpose to all make use of the 'banner' of sustainable development [99]. For practical implementations that do so, such as the IAEA conceptualisation, there is a much more nuanced view of a specific domain at the expense of broader development indicators.

2.3.2 Transitioning Towards Project-centric Indicators

Thus far, this review has aimed to raise awareness of the origins of sustainable development indicators and to demonstrate their mutability given the intention of the developers. Evaluation of off-grid electricity access projects in developing countries follows these origins and shows some evidence of transitioning from an outcome-centric to project-centric orientation in the pursuit of improving sustainability performance.

This sub-section critically reviews the key works that have marked this transition by examining their contributions towards formalising a criteria for inclusion as well as the methodological challenges with the practical implementation of indicators. A novel contribution of this thesis is the consolidation of various contributions into a revised criteria set that is suitable for project-centric sustainability evaluations.

Although the language used around sustainability varies (*success*, *failure*, *risk*, *factors*...), the common theme in the literature is a desire to use the indicators to create an informational layer that guides decision-making in order to prolong, sustain, and allow energy projects to survive for the longer-term. How sustainability is understood and measured in an evaluation is dependent upon, first, the choice of indicators and, second, the criteria for including indicators.

Challenges with Mixed Indicators

The use of mixed indicators, both outcome-centric and project-centric, is commonplace to sustainability evaluations despite have a number of challenges. These challenges are identified and discussed in this sub-section.

Perhaps the most prominent example to date that includes both elements was developed by Ilskog for energy programmes and projects in developing countries [10]. Islkog selects 39 indicators that were drawn from a bank of indicators, originally from IAEA, OECD, World Bank and UN, and then classifies these under an expanded set of five dimensions (see Figure 2.6). Indicators are described as “message carriers and facilitators for stakeholders to understand and be able to grasp results and messages of an evaluation” – since legacy indicators were aimed at the national level, the aim of the work was to revise indicators that could be applied to projects and to “investigate reasons behind the successful/less successful implementation of rural electrification" [16].

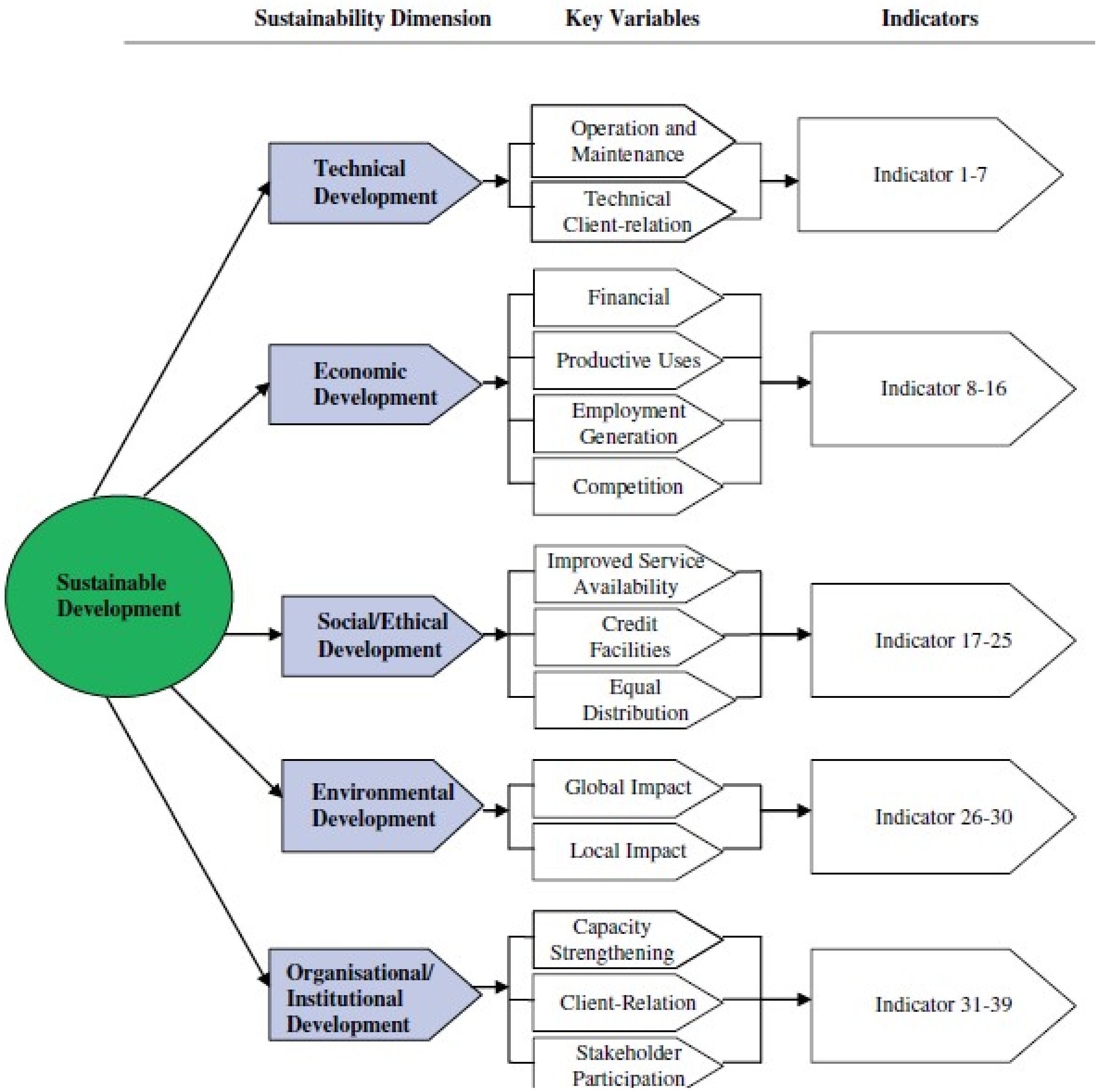

Figure 2.6: Sustainability Dimensions for Programmes and Projects [10]

Ilskog and Kjellström demonstrated the indicators in a sustainability evaluation in 2008 over seven organisations operating in Tanzania, Kenya, and Zambia [101]. Data was gathered on 31 of the original 39 indicators through a combination of interviews, inspection, and review of written documentation available for the projects. Data for each indicator, under each category, provided the basis for a numerical score that was equally weighted intra-category. Values for the scores were varied: binary (yes/no), continuous (unbounded), continuous (bounded 0 to 100). To give the scores value, the projects were ranked relative to each other for each category. Based on the composite scores of the projects, the authors find some level of sustainability for all the projects on nearly all the categories and are able to comparatively rank the projects.

Ilskog's indicators are a reflection of the author's conceptualisation of sustainability; the Ilskog definition mixes both project-level sustainability and outcomes representing local and international development goals [10]. There are examples of indicators directly relevant to a project context under almost every dimensions such as: *technical losses*, *profitability*, *any serious local environmental impact identified*, and *level of satisfaction with energy services*. A 'low' score among these indicators has a clear and present impact on a project's sustainability – in other words, they are project-centric.

Other proposed indicators lack this clear interpretation and are therefore less applicable for a project sustainability evaluation. This assertion is due to three separate critiques that are discussed below. Whether these indicators can be valued for additional reasons, outside of sustainability concerns, is not within the scope of the thesis. This critique is centred on the Ilskog indicators [10] but it is generally applicable to other studies which follow the lead of Ilskog by presenting mixed indicators.

The first critique (**type 1**) is that some indicators are relevant to the global context but not to the local context: *Emissions of carbon dioxide from production* and *Share of renewable energy in production*. Both indicators will score highly against global objectives but do not necessarily impact a given project – a hybrid solar-diesel versus a solar PV only system can be more sustainable despite higher emissions. Such indicators may also overstate the obligations of rural households in achieving the global goals. Zomers notes that "If the households of all 2 billion rural dwellers were supplied with electricity generated with an average fuel-mix the effect, in terms of carbon dioxide emission, would only add about 1% to the 2000 global emission of carbon dioxide." [102, p.75]

A second critique (**type 2**) is indicators which are selected to track extrinsic data that is usually associated with broader development indicators or research objectives.

Examples which fit within this classification are: *Share of population with primary school education (F/M)* and *Distribution of electricity client households in income groups (F/M)*. These extrinsic indicators are used to assist in describing project's context more fully but do not suggest if a project is more or less sustainable.

A third critique (**type 3**) is indicators that target a development objective with no clear feedback to the project's operations. Examples are: *Share of women in staff and management* and *Number of street lights in the area.* High scores in these indicators reflect a project's ability to meet its development outcomes or design goals, but it is unclear how they might support or detract from a given project's sustainability. It is easy to imagine a project with a zero score among these indicators, that is one which has neither female staff nor street street lights, yet still being able to thrive.

Since their inception, Ilskog's indicators have nonetheless been influential and applied to sustainability evaluations by a number of other scholars [25, 33, 71, 80, 81, 101, 103–105]. For each of these studies, the objective of evaluating the sustainability of projects is embraced but they continue to include mixed indicators – project-centric and outcome-centric concepts are not differentiated. The evaluations tend to be weighted towards outcome-centric indicators, which is at the same time a reflection of the authors' definition of sustainability.

Bhattacharyya applies a variation of Ilskog's indicators to a generic set of technologies suitable for rural electrification: grid extension, solar home systems, local mini-grid, petroleum coking fuels, biogas, and improved cook stoves [25]. The study proposes indicators such as: *Reliance on local resources*, *Cost recovery potential*, *capital cost burden on the user*, *Wider usability amongst the poor*, and *contribution to reductions in land degredation.* Similarly, Rahman et al. compare several renewable options for a 25kW system in Bangladesh [81]. Indicators used here include: *Dependence on fossil fuel*, *Lifecycle GHG emissions*, *Opportunity for private participation.*

Yadoo and Cruickshank take a similar approach as Bhattacharyya in developing a set of potential indicators and building on Islkog's indicators [80]. Although the indicators are applied to specific projects, they suffer the same ambiguity of purpose and mixing of indicator types. For example some outcome-centric indicators are: *Electricity* *is used in schools*, *Health care has improved*, and *Electricity is generated from a low carbon source*. Meanwhile project-centric indicators are: *Service is reliable, disruptions are minimal* and *System breaks even - O&M costs are met*.

Lillo et al. perform a sustainability evaluation different technology options in the context of energy-sanitation projects in Peru [71]. Indicators are based on past literature as well as community consultation. There is a mix of indicator types. Examples of outcome-centric indicators are: *Women are trained for O&M*, *Local materials have been used*, and *Reduction of energy costs (e.g. kerosene, candles, batteries*, *Increased number of hours for children's education at home*. At the same time, there is also a clear focus on project-centric indicators: *no adverse local environmental impacts have occurred*, *Service is safe to use and operate*, and *Service is reliable, disruptions are minimal*, for example.

Ribó-Pérez et al. use an Analytical Network Process (ANP) to select a sustainable design for an off-grid community in rural Honduras [105]. The ANP method is depends on qualitative inputs from experts to evaluate the complexity inter-relationships of factors or criteria involved in 'suitable' [105, p.875] project design. Like other studies cited in the section, a set of indicators are adopted, derived from other evaluations including Ilskog and toolkits (GIZ), ultimately accepting 14 total criteria. Here there are outcome-centric indicators such as *Greenhouse emissions*, *Capacity Building*, *Equal distribution of impacts*. Other indicators are project-centric: *Local energy resource availability*, *Operations and maintenance cost*, and *social acceptability*.

López Gonazález, Domenech, and Ferrer-Martí build on Ilskog's criteria and propose a method for evaluating sustainability of rural electrification projects in Venezuela [104]. The authors implement the evaluation with 15 selected indicators for 587 individual projects[9]. Despite the existence of some project-centric indicators (such as Technical *Reliability*, *Adequacy*, and *Rates Sustainability*), there is a otherwise a spread of outcome-centric that suffer from all three critiques. There was a single type 1 outcome-centric indicator *Emissions mitigation*. Type 2 outcome-centric indicators were far more com-

[9]The population of projects consisted of over 19,000 household SHS, community PV projects and hybrid PV-wind micro-grids

mon, for example: *Beneficiaries per phase*[10], *Education*, *Technological Change*. Type 3 indicators were also present: *Management model* and *Productivity*. The author's conclude that relatively high sustainability levels of the programme were achieved. This is unconvincing because most of the indicators reflect desired outcomes rather – the result instead suggest the programme achieved its objectives. Therefore, the evaluation can be viewed as another example of an impact or outcome evaluation hidden in a sustainability evaluation.

Other examples of evaluations exist which fully utilise outcome-centric indicators. Brent and Rogers develop a sustainability assessment methodology that is applied to South African renewable energy projects [79, 106]. Twenty indicators are developed and classified under the main headings: economic, institutional, ecology, sociology, and technology. Example indicators include: *Years of education for working adults*, *Tonnes of CO2 eq.*, *Nutrition*, and *Biological community diversity*. Not a single indicator that is used can be reasonably considered project-centric. The study concludes that the project considered are not sustainable. Here again there is a mixed approach to the use of indicators: the indicators are outcome-centric, but the reasons given for low sustainability are project-centric: "the lack of resilience of the technological system to demands from the social, economic and institutional sub-systems" [79, p. 264].

Indicator Framework Advancements

Even as there has been challenges to using mixed indicators, several innovations have extended the indicator framework laid out by Ilskog. These advancements are identified in this sub-section.

Lillo et al.'s evaluation of energy-sanitation projects in Peru was previously discussed but deserves a second consideration for its innovated use of absolute scales rather than rankings [71]. This attempts to address the issue when ranking scores whereby the discrete rank can tend to minimise large absolute differences in indicator scores or vice-versa. This approach supports more objectivity as it could be used to compare projects across different evaluations.

[10] The three phases of the program each had target installation counts.

A more restrictive view of project-centric indicators can be considered an innovation. Bekker and Gaunt branch out from the IAEA indicators and separate the competing sustainable development outcomes from project-level sustainability objectives [11], perhaps the first documented example. The indicators are derived from a checklist of issues ('uncertainties'), as shown in Figure 2.7. The issues are relevant to project sustainability but could be criticised for needing further development. In particular, they have no practical guidance around their use, are intended for use only during the project design stage, and lack sufficient evidence for their validity. Nonetheless, the strict use of project-centric indicators allows for a clearer evaluation of project sustainability.

MAINTENANCE
- ☑ Accessibility of site
- ☑ Technical profiency of staff
- ☑ Incidence of vandalism
- ☑ Complexity of technology

SOCIAL

Acceptability of technology
- ☑ Noise and visual impacts
- ☑ Load limitations

- ☑ Community inertia to change
- ☑ Theft
- ☑ Community perceptions of equity

ENVIRONMENTAL
- ☑ Disposal of waste, e.g. batteries

PROJECT
- ☑ Budget limitations
- ☑ Implementation speed / ease
- ☑ Corruption

OPERATIONAL

Dependant on business model:
- ☑ Revenue collection system
- ☑ Availability of seeding funds

- ☑ Operating costs

TECHNICAL
- ☑ Load growth
- ☑ Reliability of technology
- ☑ Wind / Solar resource

Figure 2.7: Bekker and Gaunt's Uncertainty Checklist [11]

A recent sustainability evaluations by Katre and Tozzi considers 4 off-grid projects in India [70]. The evaluation has a strong emphasis towards project-centric indicators. The method classifies and defines dimensions, measures, and data gathering structure more extensively than other evaluations. Although several other studies provide a justification for the included indicators, Katre and Tozzi also define a criteria with a scoring rubric [81,107]. In addition, this innovation supports a more repeatable method and a higher level of objectivity.

Indicator Criteria

This sub-section critically reviews the Ilskog criteria for indicator inclusion extends it to be compatible with a project-centric perspective.

The Ilskog criteria for indicator inclusion, shown in Table 2.4, establishes key considerations for designing indicators [10, 16]. The criteria is a purposeful attempt to formalise a method for indicator inclusion and should be considered an innovation itself. Outside the original UN indicators, no other source develops an indicator framework (in the context of electrification in developing countries) with the level of formality as the Ilskog indicators — albeit with mixed indicators as the foundation [16]. For this reason the criteria is a solid foundation for discussing choice of indicators.

Table 2.4: Ilskog Indicator Criteria (Summarised from [10, 16])

#	Criteria	Description/Meaning
1	Simple to understand and apply	Users must feel comfortable and understand the structure of the method.
2	Transparent and inter-subjective	Data is available and trace-able. The definition of the indicators is fully understood by practitioners.
3	Robust	Indicators can be easily replicable when applied.
4	Comprehensive	Indicators should cover all aspects of sustainable development.
5	Fair	Indicators should emphasise the issues of equality, covering gender sensitiveness, and effects of the development on different social groups in the society concerned. Indicators should support a comparison of projects in different areas.

There are several opportunities to respond to the observed gaps and extend the criteria to incorporate the innovations in the literature. As part of this thesis the Table 2.5 constructs a revised set of criteria for indicator inclusion. New or altered elements are highlighted blue and discussed.

The Ilskog criteria must be modified to be compatible with a project-centric perspective. First, the *comprehensive* and *fair* criteria are removed. The critiques argued in Section 2.3.2 are applicable to the criteria in Table 2.4. In particular, the type 1 critique (applicable to the global context but not local context) can be attached to the *Comprehensive* criteria. Aspects of sustainable development are global considerations. The type 2 and type 3 critique (tracking extrinsic data and no clear feedback, respectively) apply to the *Fair* criteria. The examples given (equality, gender sensitiveness) are clearly desirable outcomes of any project, but do not necessarily have a direct connection to project sustainability. A project which fails to achieve equality of impacts among different social groups may still be quite capable of thriving.

Second, the new criteria is organised under the headings of 'practical', 'valid', 'robust', and 'project-centric'. This is done for simplicity and clarity.

Third, *Defined and justified* is added to the 'valid' heading. This follows the approach taken by Katre and Tozzi [70] to accompany indicators with supportive reasoning for their inclusion. Although it is not included in the original indicators, in practice Ilskog also defined and justified indicators (with development outcomes in mind) [16].

Fourth, under the 'robust' heading, *Replicability* is retained but renamed from Ilskog's indicators. *Absolute scales* is added, following the innovation by Lillo et al., to convert scoring to absolute scales rather than ranking [71]. *Scoring Rubric* is also added representing the need to accompany scoring with a rubric to increase objectivity as demonstrated by Katre and Tozzi [70].

Fifth, under a new 'project-centric' heading, *Relevant* and *Comprehensive* criteria are added. *Relevant* ensures that indicators should only be included if they are actually related to a project's operations. The *Comprehensive* criteria requires that indicators cover all aspects of project operations. The heading and criteria are in response to the innovation by Bekker and Gaunt, which demonstrated a strict adherence to project-centric indicators [11].

2.3.3 Conclusions

A literature review of the origins and evolution of indicators for project sustainability has been presented in this section. The indicators and framework proposed under the sustainable development initiative by the UN have been a prominent influence among the scholars proposing evaluation methods for off-grid electrical project sustainability.

Table 2.5: Revised Indicator Criteria

#	Criteria	Description/Meaning
Practical		
1	Simple to understand and apply	Users must feel comfortable and understand the structure of the method.
Valid		
2a	Defined and justified	Basis for indicator relevance should be supplied.
2b	Transparent and inter-subjective	Data is available and trace-able. The definition of the indicators is fully understood by practitioners.
Robust		
3a	Replicability	Indicators can be easily replicable when applied.
3b	Absolute Scales	Indicators should utilise absolute scales when scoring.
3c	Scoring Rubric	The scoring method should supply a rubric.
Project-Centric		
4a	Relevant	Indicators should only be related to project operations
4b	Comprehensive	Indicators should cover all aspects of project operations

Project evaluations remain a critical formal component for learning on sustainability of these projects. Despite a foundation of, and continued tendency to emphasise outcome-centric indicators, practical implementation of indicators have anchored them to project-level issues. As Ilskog explained, there is a "need to identify indicators suitable on a local project level" [10].

It was shown that a transition to project-centric indicators is incomplete – mixed indicators are the norm. Nonetheless, it was argued that outcome-centric indicators are less applicable to project sustainability due to three critiques: indicators which are relevant to the global context but not the local context (type 1), indicators which track extrinsic data (type 2), and indicators that have no direct feedback to a project's operations. Subsequent evaluations have revised the Ilskog indicators and implemented several useful innovations for indicator designs.

Through the iterations of proposed indicators, several key innovations have been identified and are outlined below:

- **Use of an indicator selection criteria**: Captures the requirements for including indicators. Original set by Ilskog was comprised of five categories – simplicity, transparency, robust, comprehensive and fair [10].
- **Scoring rubric**: Increases objectivity in sustainability scores, proposed originally by Katre and Tozzi [70].
- **Outcomes versus sustainability indicator separation**: Strictly separates project-centric sustainability indicators from outcome-centric development indicators, proposed first by Bekker and Gaunt [11].
- **Absolute scales**: Combats issue of out-of-sample relevance of sustainability evaluation results by utilising indicators that can be scored on absolute terms rather than relative ranks. This issue was raised by Lillo et al. [71].

Further sections in this thesis take a relatively strict view of the inclusion of project-centric indicators versus outcome-centric, in line with the more recent trends of indicator inclusion. This is motivated by the literature review in Chapter 3 that finds many ongoing and significant project-centric sustainability issues. In addition, there is a need to simplify the analysis of the design and operational decision-making and how they interact within a project life-cycle.

Though this review has drawn a distinct line between outcome-centric and project-indicators; the role and value of outcome-centric indicators should not be considered lessened. They are essential for development projects. Many projects are established and funded on the basis that it achieves an outcome such as increased economic opportunity or access to improved facilities (educational, health, sanitation, and others). Recent work by Eales et al. have confirmed the necessity of outcome-centric indicators for evaluating the social impact of mini-grids [108]. From a development standpoint it is crucially important that metrics are established and tracked to determine if such outcomes are achieved. Furthermore, aggregating these outcomes may have a relevance at a national or international stage.

Clearly the development outcomes are premised on project survival to continue to deliver the outcomes, suggesting that whether or not a project developer implements outcome-centric indicators that project-centric indicators are an essential inclusion. The continued ambiguity in concept of sustainability threatens to undermine the learning that is needed to make deliberate improvements in sustainability. Therefore in future research, clear distinctions should be made for indicators to better clarify the intention of the two conceptualisations of sustainability.

2.4 Techno-economic Optimisations

Techno-economic optimisation is aimed at determining the optimal configuration of system components given the available resources and component costing during the project design stage. For off-grid projects in developing countries this is not trivial given the lack of data, limitations of system choices due to supply chain constraints, and development context. A system design that can lead to optimal performance with specific economic, resource, and project constraints is critical for its ongoing sustainability and to avoid or minimise reduced reliability or unsustainable costs [109].

This section reviews the literature on techno-economic optimisation methods and experiences. It captures the tools and techniques that have been used in the context of off-grid projects in developing countries – focusing on off-the-shelf computational tools. It explores practical applications through documented cases in the literature and discusses the implications of the method for project sustainability.

The review outcome supports the inclusion of techno-economic optimisation in project design as a critical process step but also documents its practical use as a sustainability modelling tool during feasibility studies. The broad use of the tool for sustainability modelling is a response to the limited availability of data and general ease-of-use. Using off-the-shelf tools risks oversimplifying the non-technical/economic aspects of a project and lowering its sustainability prospects. This gap could be addressed generally by expanding the scope of pre-feasibility modelling to include more complex project considerations perhaps considered too nebulous by other tools. Specifically, this review argues for including modules on customer price responsiveness, operator decision-making, non-technical losses, and interactions with various ownership arrangements.

Key Insights from Section

- Techno-economic optimisation of off-grid projects using software tools such as HOMER is the defacto standard for electrical component design in developing countries, typically minimising net present costs while maintaining a minimum level of reliability.
- There are a variety of methods for performing the optimisation including custom programs, advanced algorithms, simplified manual calculations, and off-the-shelf software packages; the latter is favoured in the context of off-grid electricity access projects.
- In practice, techno-economic optimisation is used to design the electrical components of systems that accompany projects intended to be developed, where the optimisation fundamentally attempts to minimise system size and costs for a given resource and electrical demand input. They are a core component of the pre-feasibility study.
- 'Projects', as opposed to 'electrical systems', are more complex – involving dynamic interactions during the project life-cycle. Techno-economic 'electrical system' design used in place of a full 'project' design is documented repeatedly. It is shown that they often do not capture the complexities of a development project.
- Over-simplification and dependence on assumptions is widespread. Techno-economic optimisations do not account for a number of non-technical components which fundamentally involve human behaviour. There are no modules for customer price responsiveness, operator decision-making, non-technical losses, or interactions with the ownership arrangements.

2.4.1 Tools for Techno-Economic Optimisations

Prominent software packages that are available for techno-economic optimisation include Hybrid Optimization Model for Multiple Energy Resources (HOMER), RETScreen, PVSyst, and System Advisory Model (SAM) [110–115]. Inputs to these typically involve component costs, technical operating parameters, and energy resource profiles (solar, wind, etc.). A least cost optimisation is performed, subject to reliability and environmental constraints. Erdinc and Uzunoglu outline the basic architecture of the HOMER software as shown in Figure 2.8 [12]. The multi-year simulation produces outputs such as net present cost and renewable energy fraction that are driven from technical performance measures like battery voltage and solar output. HOMER uses a grid search algorithm to optimise the component choice over a single year and introduces stochastic variation in subsequent years; RET screen does not publish the optimisation method but it has been shown to provide similar results for a number of system sizes [116]. Bekker and Gaunt compare a rural South African system optimised in in both HOMER and RETscreen to a custom Matlab program and find combined errors to average -7.5% and -4.2% respectively [117]. This suggests that benefits of increased accuracy from the use of custom programs are relatively small.

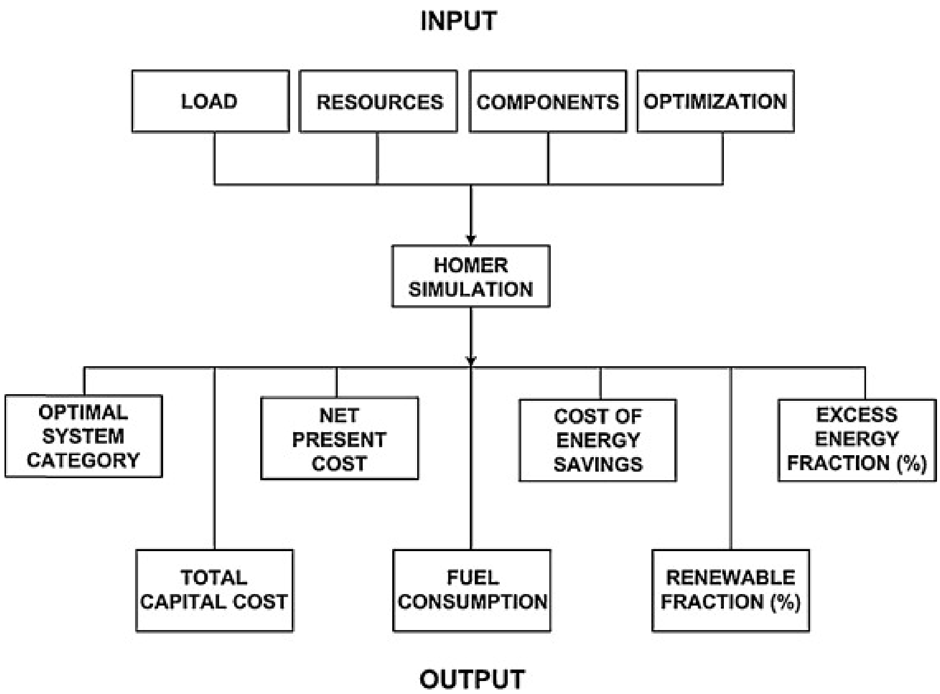

Figure 2.8: Architecture of HOMER software ([12])

Options for techno-economic optimisations are not limited to off-the-shelf software packages. The relative pros and cons of different system sizing optimisation techniques are described by Erdinc and Uzunoglu [12]. Their review covers genetic algorithms, particle swarm optimisation, and simulated annealing, ant colony and artificial immune system algorithm, among other methods. Kumar et al. and others review computational optimisations, finding examples of linear programming, artificial bee colony algorithm, mixed integer linear programming, and genetic algorithms [118–121]. Fathima and Palanisamy walk through various methods for optimising hybrid renewable energy systems, identifying the seminal papers for each method and describing the optimisations at a high-level [122]. Other researchers have manually solved for optimal systems or created custom programs to determine optimal sizing [117, 123, 124].

Although a variety of techniques are available for system design optimisation, off-the-shelf techno-optimisation and simplified manual calculations are by far the most common tools used, especially in the context off off-grid projects in developing countries [110, 125]. Therefore the remainder of the review focuses on software based methods used in conjunction with sustainability planning in developing countries.

2.4.2 Project Feasibility with Off-the-shelf Techno-economic Optimisations

Das et al. design off-grid systems in 5 regions in Bangladesh to determine their feasibility using HOMER [126]. The optimisation considered combinations of hybrid configurations including PV, battery, wind, and diesel generation. The results find systems ranging from \$0.280/kWh[11] to \$0.291/kWh. Added financial and environmental benefits are found if grid-connection and buy-back of excess PV generation is permitted. For all locations, a PV, battery and diesel system is found to have the lowest cost of energy. Das et al. discuss challenges that would impact an implementation of the design such as un-affordability, limited financial capacity to fund the design, limited technical skills and support skills, and unsupportive government policies. However, these are not considered for the system design.

Odou, Bhandari and Adamou seek to address Benin's low electrification rate by designing an optimized off-grid system suitable for the Albori Division (which has an electrification rate of 7.5%) [125]. Grid extension in Benin has been agonizingly slow and so off-grid projects could speed up electrification efforts. The authors target

[11] USD, 2021 prices

Fouay; a small village in Albori that has 333 households and is not yet connected to the main grid. After optimization, the lowest cost system selected consisted of PV, battery, and diesel and achieved \$0.207/kWh[12] (vs. \$0.22/kWh for grid connected service). An micro-hydro alternative is considered that has no carbon emissions but has a cost of energy of \$0.33/kWh due to added distribution system costs. Although sustainability considerations such as socio-cultural aspects are not addressed in the study, but acknowledged to exist, the selected system is recommended for remote areas across Benin.

Kenfack et al. justify the design of a solar, micro-hydro, diesel, and battery hybrid system for a village in Batocha Cameroon, which was found have significant hydro and solar resources [127]. The cost of energy for the optimal system was \$0.234 /kWh[13]. The unusual combination of two storage technologies (diesel and batteries) is due to relatively low seasonal renewable production over 3 months of the year. The authors conclude the following of their design: "it could be enough to take a decision concerning an electrification of a remote area in a developing country."

Al-Karaghouli and Kazmerski design a system for a health clinic in rural Iraq which selected a 6 kW solar PV system and with a cost of energy of \$0.238/kWh[14] [128]. This selected a PV and battery storage system over a diesel generator due to relatively generous solar irradiance and high price of diesel.

Kusakana, Munda and Jimoh proposed an optimally designed solar and micro-hydro hybrid system in rural South Africa involving a sawmill and household loads and compared the result against an 18 km grid extension option [129]. The cost of energy for the hybrid system was estimated at \$0.197/kWh[15] – this would break-even if the grid extension were roughly 3 km or longer.

Abdull Razak, bin Othman and Musirin design an off-grid system in Pulau Perhentian Kecil, Malaysia using HOMER [130]. The system is designed for a resort and surrounding village of around 100 households and was estimated to have a peak load of 197kW and average kW of around 50kW. The least-cost system involves a 90kW diesel

[12]USD, 2019 prices
[13]USD, 2009 prices
[14]USD, 2010 prices
[15]USD, 2009 prices

generator and 6kWh battery bank. The authors set a minimum renewable energy fraction and re-run the optimisation for a wind, diesel, battery hybrid system that has a cost of energy of \$0.296/kWh[16].

Chauhan and Saini conduct a feasibility study for a cluster of 48 villages in India using HOMER to optimise a system design [131]. Inputs for the optimisation was derived from local interviews, detailed site visits and resource potential assessments, and component modelling. Load were estimated by capturing the quantity and type of appliances and then constructing a seasonal 24-hour load profile. The authors also estimate job creation as a function of system component sizing (in kW) in order to rank the social outcome of each system. A micro-hydro, biogas, biomass, wind, PV, battery system is selected due to the least cost (\$0.092/kWh[17]) and highest estimated job creation. It is important to note that the job-creation method was not referenced nor was it included in the actual HOMER simulation. Although the resulting system was designed for the 48 villages, the authors suggest that the system would be suitable in other similar remote areas.

The reviewed literature demonstrated HOMER-based system optimisations for off-grid projects that are part of a feasibility determination. There are a host of other examples where designs are created and used to justify a system in a particular location that currently lacks electricity [132–145]. A key observation is that elements of the project sustainability, other than techno-economic considerations, are not modelled within the design. An exception was identified – Chahaun and Saini attempted to connect potential job growth to design of the system [131] – but this extension was modeled extraneous to the system design and not validated in the literature.

It was more common to acknowledge that sustainability considerations existed, but ultimately separate any potential modelling from the techno-economic design and then ignore – for example both Das et al. and Li, Lui and Li point to socio-cultural considerations for sustainability but make no meaningful attempt to incorporate how they might manifest in a project [125, 132]. Similarly, Bekker and Gaunt acknowledge social and institutional uncertainties but decline to incorporate this aspect in their

[16]USD, 2010 prices
[17]USD, 2016 prices

model [117]. Akinyele, Rayudu, and Nair, for example, explicitly state that the objective of their study for an off-grid community in Nigeria to examine the "social, technical and economic aspects... to achieve long-term viability" [143]. The resulting analysis defines a relatively detailed technical system plan, the design for social sustainability is superficial but is, nonetheless, deemed sufficient for the authors to expect a "continuous and cost-effective power supply" (*ibid*). Kumar et al. repeatedly introduce non-technical design issues (for example: local technical capacity building, community ownership structure) and make a plan for sustainability yet depend heavily on the technical design results [144]. Alzola et al. design a toolkit for Senegal to address key issues such as lack of "implication from local authorities... adequate maintenance procedures, materials and local expertise... monitoring procedures" [145]. As before, a detailed techno-economic design is produced by the authors while relegating other issues to assumptions to be achieved prior to installation.

2.4.3 Conclusions on Techno-economic Optimisation and Project Design

'Projects', as opposed to 'systems', involve more complexity – dynamic interactions which occur during the project life-cycle that make or break a project's success. Tools that focus on the development of a techno-economic 'electrical system' design used in place of a whole 'project' design omit key human-centred system dynamics that limit their usefulness to make accurate predictions of project sustainability. An 'electrical system' here is defined as consisting of various physical hardware and assets, which inter-operate to produce a system behaviour based on the physical laws of science, which differs from a 'project' which is an expanded system that involves the electrical system, but also relationships describing the behaviour and interactions between different human actors, their interaction with the electrical system, and how the electrical system's output influences their behaviour. Insights from earlier in this Chapter suggest additional factors for sustainability modelling besides those included in prototypical techno-economic optimisations.

Whether as an intention, or not, techno-economic optimisation studies are used as defacto sustainability models – many authors go on to recommend a select system from the results for implementation. Kenfrack et al.'s conclusion that the optimisation result alone "could be enough to take a decision concerning electrification" [127] demonstrates the position taken by many project developers using such tools. The results of a techno-economic optimisation present reliability and economic forecasts, in the form of energy shortages and net present costs calculations, that are based on considerable data inputs and extensive simulations. However, they are only as accurate as the assumptions held.

However, while the use of these tools is pervasive in project feasibility assessments, awareness of techno-economic design limitations and the risk this poses for project sustainability is made quite explicit in the literature. Kumar et al. note that "Past experiences show that a large number of off-grid electrification projects fail because focus is generally on technical installation without paying sufficient attention to the long-term sustainability" [144]. In their sustainability analysis of off-grid systems in South Africa, Brent and Rogers argue that "disregard at the design stage for almost all of the nontechnical aspects has further resulted in an overall unsustainable system" [79].

However, as was noted earlier, the non-technical/economic complexities were considered important but not modelled. 'Socio-cultural' aspects were given as an example, but there is no immediate reason to limit it to this factor alone; the sustainability factors captured in Sections 2.1 – 2.3 have been argued to be important to project sustainability. It is logical then to expect that failure to incorporate this complexity within the model introduce increased risks of unsustainable projects.

Although the intention for many techno-economic optimisations, as well as the software packages that are developed, may be narrow: minimise energy costs for a gradient of component sizing options – the reception by practitioners is broad, as evidenced by their continued acceptance in feasibility studies. Projects are implemented on the basis of the techno-economic designs despite a disregard of complexity. This is a disconnect between the real-world environment in developing country applications and the modelling environment of off-the-shelf software packages.

While many such non-technical aspects are known, little attempt to incorporate this into an integrated model has occurred. As is shown in Chapter 3, non-technical issues such as community acceptance, user training, skills development were established and could be considered for more detailed modelling.

Several examples of the modelling disconnect are readily discussed; consider first customer price responsiveness. In a techno-economic optimisation, it is assumed that the modelled load, say a residential customer, will be willing to buy energy from the project at any rate. Although customer willingness and ability to pay is an accepted issue in the context of energy access, there are no examples in the cited literature where customers have an ability to express their demand for energy. The input load curve remains static whether the calculated net present cost, and price floor for sold energy, is \$0.10/kWh or \$1.00/kWh. For this assumption to hold, there would need to be no alternatives to electricity, inelastic demand, and sufficient ability to pay at higher rates – an unrealistic assumption given an implementation of the designed projects are often the first access to electricity for communities.

Further considerations include the role of operator decision-making and non-technical losses. In a techno-economic optimisation model, dispatch control methods are built into the logic of the system. However, many systems require operator control actions, maintenance interventions, repair, refuelling. These aspects interact with the supply chain and require careful planning – fuel must be available and stored, replacement parts and skilled labour must be sourced, and maintenance schedules must minimise downtime. Moreover, load acquisition, growth and retention require operators to be skilled in marketing, customer service, and retail load management – all items which can be attributed to non-technical losses, but non of which are included in standard techno-economic optimisation. Instead a more realistic proposition is a project which struggles to find and retain qualified operators, keep surplus inventory, and establish business routines that engender efficient operations.

A last example is the interactions with potential ownership models which are not captured in techno-economic optimisations. Studies routinely mention an apparent role for community involvement in a project in the context of co-creation and management of off-grid development projects. Yet ownership arrangements, shared decision-making between community, operator, and funding source, and expectations for type and quantity of electricity service are omitted from techno-economic modelling. In practice, community interaction with a project is commonplace and far from a simplistic role as consumers. Community support may provide unexpected financial support as the community may not be willing to let a project fail. It may also generate resentment, jealousy and upset the local power balance. Community stakeholders may have personal or biased motivations for the project, potentially interrupting productive decision-making.

The logical response to this disconnect is to revisit and add the necessary complexity to design methodologies to account for real-world issues faced by the projects. This challenge is addressed, to some extent, in this thesis in Chapter 4 and future avenues of modelling are discussed in Chapter 7.

2.5 Chapter Conclusions

A more complete understanding of the term 'sustainability', in the context of off-grid electricity access projects in developing countries, was established in this Chapter. A concise discussion of the contributions of the Chapter is provided below. The contributions consist of defining sustainability, reviewing three key areas of sustainability literature that are used throughout the life-cycle of off-grid projects, identification the gaps within the literature, and proposals for specific research to fill those gaps. The proposals are developed further in later Chapters.

In Section 2.1 a project-centric definition for the term 'sustainability' is developed. The origins and common usage of the term are reviewed, especially as sustainability has been applied to off-grid electrification projects in developing countries. There is a clear legacy of the term stemming global development initiatives which is outcome-centric. It is argued that established definitions lack structure and clarity for the context. Common themes in the literature are: continually added emphasis on the local context, use of indicators to define the usage of the term, and self-sufficiency. A revised definition is proposed that builds on the practical usage is: "an off-grid electricity access project's ability to endure within the local context". The definition is accompanied by structured series of characteristics: internal operations versus external considerations, established performance metrics, local versus distant external considerations, avoiding beneficial outcomes, and no pre-defined end-state.

In Section 2.2, off-grid electricity project sustainability toolkits are identified that have been prominently published by major development organisations. Guidance for electricity access projects in developing countries is provided in each toolkit which include specific recommendations for sustainability. The toolkits are prominent in the literature and used by practitioners to design projects and programmes. The review identifies seven gaps in the toolkits and recognises that some toolkits express these gaps less than others. As a whole, toolkits need to be re-oriented towards life-cycle sustainability issues (especially with the inclusion of operational phase considerations), better utilise a broader evidence base, and incorporate metrics that support more robust sustainability guidance/evaluation. A new toolkit is proposed that responds to the gaps and extends the functionality of existing toolkits. Design stage enhancements are: minimum sustainability standards, recognition of sustainability gaps, identification of project innovations, modelling of measurable indicators, and ensuring that indicators are balanced among the sustainability themes.

Section 2.3 presents and discusses the origins and effectiveness of modern sustainability indicator frameworks to capture project sustainability, primarily through evaluations. Indicator frameworks remain linked to the sustainable development origins (outcome-centric), though some aspects have evolved pragmatically, such as the use of a criteria for the selection of relevant (project-centric) indicators. Use of mixed indicators remains common. This section captures the current best practices, identifies innovations on the use of indicators, and argues for improvements to address the identified gaps. Innovations include using a indicator selection criteria, implementing a scoring rubric, strict use of project-centric indicators, and using absolute scales for scoring. A contribution of this Section is a proposed set of criteria for indicator inclusion that incorporates the innovations.

In Section 2.4, the approach of techno-economic optimisation of system design to ensure sustainability of projects is explored. Software aided design off-grid projects is now a standard. The approach leans on the technical aspects and ties in financial modelling but requires strong assumptions for aspects (social, organisational, economic) outside the technical space of project design. Although the approach provides a convincing result, the remaining aspects of project design that interact with the techno-economic systems remain largely disconnected from modelling. A narrow role of the approach, limited to the laboratory setting, is contrasted against a wider role where other sustainability aspects are more explicitly modelled alongside technical and economics aspects. Current limitations of the approach are identified and provide the basis for the modelling work of this thesis in Chapter 4.

Chapter 3

Sustainability Experiences with Off-grid Electricity Access Projects

This Chapter reviews the current literature involving sustainability experiences of off-grid energy projects in developing countries. The purpose is three-fold; first, to build up an understanding of the sustainability levels of the current stock of projects and to classify the individual issues under the sustainability categories: economic, organisational, technical, social, economic, and external. Contrary to the popular narrative of sustainability, this review finds significant problems still not addressed even in recent documentation. The overlap of varying types of issues within projects and when captured as a whole indicate a complex interrelationship of issues. The second purpose is to develop a more qualitative and deeper view of these interrelated issues. The third purpose is to highlight the fragmentation of understanding of sustainability in the context of these projects. It is reasonable to expect that different sustainability issues manifest in different off-grid contexts, for example from variations in the demographics and culture of populations, geographic idiosyncrasies, and differences in the underlying institutional framework in the country. Nonetheless, a rigorous structure that can capture these variations for evaluating sustainability experiences remains elusive.

In Section 3.1, the literature for individual projects which specifically address sustainability issues are drawn primarily from the following journals: *Energy Policy, Renewable and Sustainable Energy Reviews, Energy, Applied Energy, Renewable Energy, Energy for Sustainable Development, Sustainable Energy Technologies and Assessments*. Relevant literature includes all off-grid electricity projects in a developing country that also involve specific analysis on the sustainability of the underlying projects or discussion of the methodology. The Section records specific sustainability issues that are reported in each source. An analysis follows which provides a broad review of ongoing sustainability challenges. In Section 3.2, detailed case studies taken from the author's experience in Malawi, Gambia, and Kenya are described. These provide an opportunity for a more detailed narrative of the complexity of sustainability issues in off-grid projects. The case studies support the broader analysis in the previous section. Additionally, two complexities are described in the case studies that are later incorporated into the thesis model in Chapter 4: demand driven by the community relationship to the project and operator skill levels.

3.1 Review of International Experiences

This Section reviews wider project experiences involving small scale electrical projects in developing countries. The purpose is to establish a more comprehensive understanding of factors affecting sustainability of projects, capture the interrelationships between sustainability factors, and to build a sense of an overall level of sustainability or failure achieved. The approach is to review individual projects from the literature as well as summary studies that draw out learning from multiple projects. The literature review covers 24 specific articles involving over 21 countries over the time period: 2001 - 2018.

3.1.1 Literature Review Methodology

The thesis takes a two-pronged approach to reviewing the literature on sustainability issues of off-grid projects in developing countries. First, it reviews the existing literature selected from scientific journals, peer-reviewed conferences, and grey-literature from organisations with off-grid development project experience. This approach conducts a meta-analysis of the selected literature. Second, three separate case studies are reviewed qualitatively. As the author was responsible creating the primary research data, these case studies offer a deeper view into the complexities of off-grid projects and the sustainability challenges which are faced.

Review of Existing Literature

The review of existing literature draws from the following journals: *Renewable Energy* [7], *Renewable and Sustainable Energy Reviews* [3], *Energy Policy* [2], *Applied Energy* [2], *Energy for Sustainable Development* [2], *Progress in Photovoltaics: Research and Applications* [1], *Sustainability* [1], *Energy Sustainability and Society* [1] *African Journal of Engineering Research* [1]. A single reference is cited from the IEEE Power and Engineering Society's *Global Humanitarian Technology Conference (GTHC)* [1]. Additional references are identified from grey literature: *World Bank* [1], *Electra* [1], and *HYSTRA* [1].

The articles were selected with two conditions. First, they concerned off-grid electricity access projects in a developing countries. Second, they needed to include either a dedicated analysis on the sustainability a project or a discussion of the methodology of determining sustainability. Search queries to identify articles included: "electricity access", "off-grid", "project", "rural electrification", "developing countries", "sustainability", "evaluation".

The journals were selected due to their current or historical foci of off-grid electricity projects or sustainability. Additional journals were considered such as *Energy*, *Sustainable Energy Technologies and Assessments*, but had no articles identified by the author that met the conditions stated. The search was conducted in SCOPUS, IEEE Xplore, and Google Scholar.

A meta-analysis is performed upon the identified articles which includes a qualitatively identifying sustainability issues reported by the authors. The analysis that follows provides a broad review of ongoing sustainability challenges, reveals the level of concentration of issues per high-level sustainability factor, and captures the wide-range of challenges facing projects.

It is worth noting some of the challenges inherent in the literature when reporting sustainability through evaluations and assessments. Sustainability reporting is difficult and uncommon due to high costs (of reporting), logistical challenges, and being considered non-mandatory in most projects that tend to instead be focused on documenting impact rather than sustainability. Additionally, the inherent biases of authors, who will usually have a stake in the project outcomes, mean that a certain degree of subjectivity must to be expected. It is not possible to determine the extent of bias which may be present so the conclusions have to be investigated carefully. Lastly, the documentation tends to focus on best practices and 'successful' projects rather than challenges and failures. Project learning from many such failures are never published; it may be fair to assume that the results in this Section under-represent the scale of sustainability issues.

Review of Case Studies

The case studies that are reviewed are: the Malawi Renewable Energy Acceleration Programme (MREAP), the Kilowatts for Humanity Muhuru Bay micro-grid (KWH-MBMG), and the University of Strathclyde Gambia Project. Each are united in the commonality that the thesis author was involved in the capturing of primary research data and, in turn, this has provided an opportunity for discussing the complexities of sustainability in projects. Each case study's research methodology are discussed here.

The **MREAP case study** is captured in Section 3.2.1. This case study conducts a literature review using project reports in addition to the academically published literature. The review focuses on the sustainability elements identified within each source. The design of MREAP entailed exploring community energy models to improve sustainability and impacts, making it an ideal case study to explore the topics of the thesis.

The **KWH-MBMG case study** is captured in Section 3.2.2. This case study utilised interviews, audit of project log books, and direct measurements of power system data. Interviews were conducted in English and held with the project owners (2), current operator, and five customers. Customers were selected through snowball sampling primarily due to the short time frame of conducting interviews, amongst other activities, and difficult terrain required to physically travel to each location. All interviews were held at the interviewee's household apart from the operator, who was interviewed at the project kiosk.

Since the interviews focused on the business and power system performance of the project, there were no major ethical considerations from the use of sensitive information. Nonetheless, all those interviewed were informed that they were not required to participate and could stop the interview at any time if they felt uncomfortable. All participants agreed to the interviews and participated fully.

The field visit gathering data for KWH-MBMG case study was conducted over a three day period in the village of Muhuru Bay, Kenya. Data was triangulated from the multiple interviews, direct readings taken from the system, direct observations and accounting work on the project. Interviews were semi-structured, with a pre-developed list of questions and it was assumed that the questioner would be able to probe further if needed. This flexibility was necessary since the full extent of the problem facing the project was not yet known. Since there was advanced knowledge of an incident of theft (by the project operator – who later left), it was possible to develop a series of questions around this topic. Additionally, questions were developed around the technical and financial performance of the project. Interviews were led by the author who took notes along with another field researcher who was primarily focused on the technical system health checks. Each evening while in the field, notes were compared between the researchers and any further topic areas were developed into follow up questions or activities.

After capturing the research data, initial sustainability conclusions were discussed with the project owners and a corrective action plan was jointly developed. Following the field work, the author produced a summative report of the sustainability status of the project which was reviewed and confirmed by the other field researcher. The report was then delivered to the sponsoring organisation (Kilowatts for Humanity) and the project owners.

It is important to acknowledge the biases which may have impacted KWH-MBMG case study results. First, as Kilowatts for Humanity had sponsored the trip and funded the programme activities, there was an inherent bias to shed the project in a good light. However, the thesis author was not (at the time) affiliated with the project and had no further funding opportunities available. Furthermore, since the study's premise was to explore the sustainability challenges, it can be concluded that Kilowatts for Humanity truly desired critical feedback. Thus, the potential for this bias to impact results was considered minimal.

Second, respondent bias was a potentially present as respondents may have had a variety of reasons to avoid sharing full details of the project sustainability situation, including: owner and operator desire to ensure ongoing support from Kilowatts for Humanity (both financial and technical support), customer desire to maintain consistent service, as well as the desire by the owner to uphold their reputation despite the publicly visible problems being faced. Mitigating this potential bias was handled through several methods. The researchers relied on data triangulation, as described previously, to ensure the underlying data was accurate. The first stage of data gathering involved the review of the financial records and gathering observational data. Hence, when conducting interviews the researchers were well prepared to present decisive data – which limited opportunities for deception. At the onset, it was made clear to all participants in the study that Kilowatts for Humanity support would continue regardless of the conclusions made. The researchers tried build a sense of trust during the visit – the provision of training was included during the visit and a corrective action plan was created to reassure all involved. Additionally, care was taken to involve the owner and operator in the decisions made as a result of the study, ensuring their engagement. These measures were considered sufficient to reduce potential respondent bias.

The **University of Strathclyde Gambia Project case study** is captured in Section 3.2.3. This case study utilised interviews, audit of project log books, and direct measurements of power system data. The thesis author was responsible for supervising several undergraduate business students. All interviews with local partners were held at one of the seven project locations. These were held exclusively with the project operators at the site (3) and conducted in English. Additional interviews were held with the University of Strathclyde project support team (3) who were themselves responsible for the technical maintenance of the systems and had knowledge of the support arrangement.

The interviews with local partners focused on the business and power system performance of the project. The interviews with University of Strathclyde staff focused on power system performance and the support arrangement. As a result, there were no major ethical considerations from the use of sensitive information. Nonetheless, all those interviewed were informed that they were not required to participate and could stop the interview at any time if they felt uncomfortable.

Interviews with local partners were semi-structured, with a pre-developed list of questions and it was assumed that the questioner would be able to probe further if needed. Questions were drafted with the students and other University of Strathclyde staff following a literature review of the sustainability literature and revolved around the financial and technical health of the project. As there were few details around the status of the projects prior to arriving, flexibility was necessary to ask additional questions as issues arose. Interviews were led by the author who took notes along with students. Each evening while in the field, notes were compared between the author and students and any further topic areas were developed into follow up questions or activities.

Interviews with University of Strathclyde staff were semi-structured, with a pre-developed list of questions and it was assumed that the questioner would be able to probe further if needed. The pre-developed questions revolved around the maintenance regime, ownership arrangements, and decision-making authority of local partners and the University of Strathclyde. These interviews began prior to the field trip and were repeated to ensure accuracy and understanding as the situation at each location was better understood.

After capturing the research data, initial sustainability conclusions were discussed with the students and University of Strathclyde staff. Following the field work, the author supervised a report of the sustainability status of the project which was reviewed and confirmed by University Staff. The case study in this thesis was written separately from the student work, but shares similar themes.

It is important to acknowledge the biases which may have impacted University of Strathclyde Gambia Project case study results. First, as the author was a staff member at the University of Strathclyde, there was a potential bias for the research to reflect positively on the project. Additionally, the projects were donor funded and so it was important to the University (and donors) that the funding continued to have a positive impact upon the beneficiaries. However, prior to the case study, the ongoing sustainability challenges had been identified, though not fully explored. Given the intent of the author's doctoral research was to explore sustainability issues in off-grid electricity access projects, it was felt by the author that there was ample room to provide a critical review. Indeed both the student report and this thesis offer constructive criticism on the project and suggestions for improving the sustainability outcomes.

Another potential bias would originate from respondents, particularly as they desired to ensure continued support from the University. Data triangulation with the log book audits, power system measurements and observations, helped to mitigate the potential for obviously misleading responses. As discussed in the case study which follows, most of the systems were poorly maintained and were on shaking financial footing and as a result, heavily dependent on the University for support. This reality had been the case for over five years for some projects prior to the data gathering associated with case study. In other words, the dependent relationship had long been established and not, in the view of the author, considered to be a factor in future support from the University. As a result, this potential bias was not considered to significantly affect responses.

3.1.2 Projects in the Literature

To assist in this literature review, this Section adopts the Chapter 2 definition of project-centric sustainability and attempts to organise issues as identified by the original authors under key sustainability categories [<u>**labelled bold and underlined**</u>]. For clarity, sustainability issues that have slightly different wordings have been grouped under single labels. Although the definition that is used stems from the constructed definition from the indicator frameworks and sustainability toolkits after critique (see Chapter 2), it is reinforced by the experiences in this Chapter.

The frequency a particular sustainability issue is mentioned is shown within Figures 3.1 to 3.5. A full summary of the found sustainability issues, by category, is shown in Appendix A.2. The analysis which follows draws out the relative frequency of issues faced by projects and sheds light on how widespread and interconnected various sustainability issues are.

Multi-country evaluation projects in Sub Saharan Africa - Ikejemba et al.

In 2017, a review in 9 Sub Saharan Africa countries used interviews and direct observations to evalute the sustainability of 29 projects consisting of off-grid village electrification, public facilities, streetlights and other public infrastructure. It found that roughly 90% had experienced some degree of failure [146, 147], though the distribution of issues amongst underlying projects was not reported. Contributing factors to these failures included poor political support **[external]**, corrupt awarding bodies **[external]**, poor ownership **[organisational]**, poor coordination between stakeholders **[organisational]**, insufficient project planning **[organisational]**, lack of maintenance systems **[technical]**, public exclusion **[social]**, and low levels of support and engagement **[social]**.

Multi-country evaluation - Terrapon-Pfaff et al.

Terrapon-Pfaff et al., reviewing 23 renewable energy development projects in 17 countries, found nearly 21% failed or partially failed and only 48% were fully functional [85]. Factors contributing to the poor sustainability of these projects were cited as lack of user ownership **[social]**, low user satisfaction with the technology **[social]**, external influences (political, institutional, environmental) **[external]**, and problematic logistical situations **[external]**.

Early multi-country evaluation - Nieuwenhout et al.

In a widely cited study by Nieuwenhout et al. in 2001, the authors conduct a literature review on 104 case studies of solar home system (SHS) deployment [148]. Many problems were found including insufficient project institutional frameworks, in particular lack of user commitment and insufficient maintenance. In the case of Guatemala, nearly 45% of installed SHS had serious issues such as limitations from users to repair basic failures **[social]**, lack of savings made for future battery replacement **[economic]** due to cultural tendencies **[social]**. Reviewed SHS in Kenya, Zimbabwe and China found that 10-21% were out of operation due to an unfeasible financial model **[economic]** and lack of an after-sales maintenance service **[organisational]**. Further failures were due to the mis-design of the original systems (under-sized) **[technical]**, user-led replacement of failed components with inferior counterparts (insufficient user training) **[social]**, lack of preventative maintenance **[organisational]**, and prohibitively expensive cost of transport for skilled technicians to attend the systems **[external]**. Charge controllers which malfunctioned **[technical]** and bypassed low-voltage disconnects (poor installation quality) **[technical]** were major reasons for failed batteries. Finally, lighting, which is one of the major load categories for most off-grid systems in developing countries, were found to have substantially different failure rates depending on the quality of lighting used (in some cases 10x higher for certain lamps) **[technical]**.

Multi-project historical study, Chaurey and Kandpal

In 2010 study, Chaurey and Kandpal review successes and challenges of rural PV based electrification programmes dating back from the 1980s [149]. This review echos some of the challenges of scaling and sustainability experienced within the World Bank rural electrification activities such as poor quality components and maintenance **[technical]**. Additional sustainability factors found include user attitudes **[social]**, level of technology marketing **[organisational]**, and level of user training **[social]**. Inappropriate design **[technical]** was also argued by Akinyele and Rayudu [150] who clarified that poor resource estimation **[technical]** and system design not following standards **[technical]** can be a sustainability issue.

Urban Electrification Challenges, Rojas and Lallement

Rojas and Lallement [151] summarise a practitioners workshop on electrification of urban slums in developing countries. Although there are differences in the context of rural versus urban electrification efforts, some cross-cutting issues are relevant. Issues affecting the long-term sustainability, in particular the inability to cover systems operations and maintenance costs **[economic]**, were a factor for limited investment in this area. Two major problems during the design of the project were the lack of knowledge of the targeted communities **[social]** as well as analytical tools to evaluate the extent to which the project can be upscaled **[organisational]**.

Programmatic considerations of Solar Home Systems, Vlueten, Stam and Plas

Vlueten, Stam and Plas in provide a critique of programmes involving solar home systems in particular those which exist on a project basis rather than through “self-organisation” [152]. Self-organisation refers to organisation within the framework of a commercial market, whereas project based is externally organised, for example through a grant-funded project. The authors conclude that programmes which are self-organised, for example in Kenya, Morocco, Sri Lanka, Tibet and Zimbabwe have been highly successful and reaching up to 5% of rural populations as of 2007. A major factor for the sustainability of the self-organisation model stems from the existence of a developed supply chain **[external]** which reduces operations and maintenance costs and encourages longer-term relationships between distributors and customers **[social]**. The authors contrast this with externally organised projects which are distinctive by the involvement of donor organisations, complex arrangement, and high organisational capacity requirements for the implementer **[organisational]**. The many weaknesses of this model include: limited availability of equipment **[external]**, subsidisation of the equipment and expectation by users for subsidisation **[social]**, temporary nature of project and relationship between delivery organisations **[organisational]**, limited after sales support **[organisational]**, and need for high capacity building to be built into the project **[external]**. This paper suggests that much of the sustainability issues of solar home system deployment emerge failure to adapt to the local conditions as defined by the organisation of the market.

Evaluation of Cooperative Models, Yadoo and Cruickshank

Yadoo and Cruickshank conduct a sustainability evaluation of cooperative based rural electrification efforts and identify some sustainability challenges often experienced [33]. Their research found that private-based projects that poor service quality **[technical]** affects the customer willingness to pay and has been a barrier to successful projects. Additionally, the low profit margins **[economic]** experienced in Mali, Morroco, and South Africa was cited as an obstacle which reduces local entrepreneur involvement **[organisational]**. A cooperative model, as opposed to a private model, involves the formation of a local cooperative to manage rural electrification in a certain area. Cooperative ownership **[organisational]** was credited in rural electrification in Nepal as key to improving the transparency of the electrification activities, involving local decision makers, increasing local investment, increasing awareness of electrification, reducing system losses from 25% to 10%, and reducing incidents of unpaid bills. Meanwhile, several general sustainability issues were noted. The cooperatives were hampered by loss of experienced personnel **[organisational]**, highlighting the need for systematic training and staff retention strategies **[organisational]**. As the management organisation grew, it became more vulnerable to local power dynamics **[social]**.

Multi-country sustainability evaluation, Terappon-Pfaff et al.

In two related studies Terappon-Pfaff and co-authors [85, 153] evaluated the impact and reviewed the sustainability of 23 small scale renewable energy projects at the 12 – 24 month mark following installation. The projects covered all manner of renewable energy technology and a wide array of applications. A questionnaire was implemented with these projects which captured information related to the overall project sustainability, technology, social and economic aspects, environment, replication and policy development. One overall measure, the degree to which the technology was still functional, discovered that only 48% of the technology was fully functional, 30% mostly operational, and 22% either limited or completely non-functional. The studies focused primarily on success factors, but sustainability issues encountered included level of technical functionality **[technical]**, level of financial viability **[economic]**, existence of effective management **[organisational]**, external factors (including institutional, environmental, and policy conditions) **[external]**, and problematic logistics **[external]**. The most positive influences on project sustainability were found to be local availability of maintenance and repair services **[organisational]**, trust and reliability between implementing organisation and other stakeholders **[social]**, local ownership **[social]**, user satisfaction with technology **[social]**.

Grameen Shakti experience, Amin and Langendoen

Grameen Shakti, which offers a portfolio of SHSs and compatible appliances in Bangladesh was reviewed by Amin and Langendoen [154]. Key sustainability factors cited by the authors for the deployment model include use of innovative financing **[economic]**, free maintenance scheme for owners **[organisational]**, inclusion of a low-cost warranty **[organisational]**, a relatively well developed set of consumer friendly practices (e.g. dead battery removal) **[organisational]**, linking energy provision with income generating activities (IGAs) **[economic]**, strong audit culture **[organisational]**, and offering of initiatives which incentivise and empower social impacts (e.g. promotion of education, women's capacity building, and creation of local jobs) **[social]**.

Bangladesh Experience - Urmee et al.

Urmee at al. reviewed the sustainabiltiy of Solar Home Systems (SHS), primarily from users in Bangladesh [155]. In particular, the study highlighted the need for socio-cultural understanding and knowledge of policy issues during off-grid electrification, and ensuring solutions are designed to meet the actual (and not perceived) community need. Social issues that were important to sustainability included appropriate solutions to the socio-cultural context of the community **[social]**, community participation in the project **[social]**, and having an awareness of the cultural attitudes of the communities **[social]**. Local after sales services were necessary **[technical]** along with development of local skills **[organisational]**, and establishing and advocating for an enabling political environment **[external]**. The findings follow earlier studies by Urmee and Harries [156,157] which capture a wide range of sustainability factors including designing systems which do not need subsidising **[economic]**, having readily available spare parts **[external]**, training for users **[social]** and technicians **[organisational]**, and ensuring components are high quality **[technical]**.

Rural Electrification in Ecuador, Feron, Henrichs and Cordero

The sustainability of rural electrification efforts in Ecuador is captured in a 2016 study by Feron, Henrichs and Cordero [158]. In Ecuador, grid extension has been government-led while off-grid efforts have been relatively underfunded – only 1.86% of funding went to off-grid from 1998-2009. Additional international funded efforts targeted off-grid communities, though by 2009 only around 10% were still in use. Another 3,270 stand-alone PV systems installed since 2009 by other organisations were subsidised and required outside financial support to cover operations and maintenance. Uncertainty from the adoption of seven different constitutions **[external]** since 1938 (with the latest in 2006) has disrupted the availability of information on national programmes and application of policies, and resulted in lack of project ownership. Sustainability challenges facing these projects were lack of supplies in rural areas **[external]**, limited skills to conduct repairs **[organisational]** that resulted in compromised system reliability. Higher long term costs and low revenue generation made many projects not economically viable **[economic]** without outside financial support. At the heart of the challenge is the limited ability to pay for energy **[economic]** by users, and over-sizing systems **[technical]**. Overly sophisticated systems were potentially cited as a problem for newer micro-grids that would be locally managed **[technical]**. Environmentally, old battery disposal for stand-alone PV systems is inconsistent and in some cases they are buried, potentially causing pollution **[environmental]**. Efforts throughout the country have taken different approaches to gaining social acceptance. In some cases there has been rejection of the programme by indigenous leaders **[social]** and other cases where acceptance has been much higher.

ZESCOs in Zambia, Lemaire

Three off-grid fee-for-service companies setup in Zambia, or ZESCOs, were evaluated by Lemaire against sustainability criteria such as commercial success and technical problems [61]. With respect to finances some non-payment has occurred **[organisational]** and cost-recovery has been hampered by uncertain macroeconomic conditions **[external]** (devaluation of the local currency). At the time of the evaluation, ZESCOs were under financial strain due to competition with grid connections, changing the economics of the model as they had to compete with the subsidised power supply **[economic]**. Technically, only 47% of systems were operational a decade after installation. Specific technical reasons for this include a combination of battery quality problems **[technical]**, problems with the metering equipment **[technical]**, and a persistent over-use of systems **[social]**. Despite these issues the opportunity for the ZESCO model was seen as optimistic if the could make several key improvements: added local training, improving operator-user relationships, and application of equal subsidy levels for off-grid compared to on-grid connection. Lemaire attributed "strong social control", or, familiarity between customer and ZESCO staff **[social]**, as a a contributing factor for the lack of vandalism and low theft rates experienced [61].

Nigerian off-grid, Akinyele, Rayudu and Nair

In Nigeria, a project design exercise undertaken for a remote mini-estate identified several sustainability challenges [143]. First, initial financing for the renewables based system was relatively high versus a diesel based system, which would prevent the investment **[economic]**. Second, the low financial status of users (low ability to pay) undermined the economic feasibility of a potential project **[economic]**. Third, a legacy of poor system design **[external]** and lack of standards **[external]** in the area has made potential users wary of the technology, resulting in lower demand than expected. Fourth, a history of past projects not having sufficient maintenance **[organisational]** process resulted in many system failures. Fifth, the local land ownership issues, which would require permission and approval from local authorities, was not secured by the project and was seen as a potential obstacle **[external]**. Sixth, uncertainty in load growth and load shifting behaviours by the users **[technical]** and, furthermore, readiness of the operators to manage the system following such changes **[organisational]**, was seen as major issues affecting design.

Solar Home Systems in Assam India, Barman et al.

A performance and impact evaluation for solar home lighting systems in Assam, India in 2017 found that only 28.9% of the systems were found to be fully functional [159]. The study implemented a comprehensive questionnaire to 544 households in the area where the overall number of installed systems is estimated at 40,035. Systems were installed between 2006 and 2014 and the questionnaire was implemented in 2014. A wide range of technical faults were documented: CFL blow outs and other minor issues (62% of households), major issues such as charge controller failure or partial battery failure (1.6%), and some units completely non-functional (7.2%) **[technical]**. Overloading due to insufficient solar resource and heavy system usage was found in 9.8% of households **[technical]**. Additionally, users had bypassed charge controllers when aiming to get more out of the batteries **[social]**. Installation of modules aggravated energy shortage issues as 33% of modules were found to have shading effects **[technical]**. In fact, many installations were carried out by the users themselves, without any formal training **[organisational]**. After-care for systems was limited as the authors found the managing Village Energy Committees were woefully lacking in capacity for setting up service centres **[organisational]**, securing spare parts **[external]**, providing awareness to customers on usage **[organisational]**, and training local technicians **[organisational]** for ongoing maintenance.

Off-grid project in South Africa, Brent and Rogers

Brent and Rogers conduct a sustainability assessment of an off-grid project in Eastern Cape Province South Africa implemented in 2007 [79]. The analysis considered both impact and project-level sustainability issues. A range of sustainability problems were found in this project: instances where users bypassed power limiting switches **[social]**, excessively high initial capital costs **[economic]**, system overloads **[technical]**, disputes between parties and breakdown of trust **[social]**, unplanned generation disconnections **[technical]**, and low ability of the project to make adaptive changes to challenges **[organisational]**. The authors conclude that better implementation of the principles of trans-disciplinarity, resiliency, complexity, adaptive management, and adaptive capacity to such projects should improve future results.

Off-grid project in the Phillipines, Hong and Abe

Hong and Abe investigate the sustainability of an off-grid project the Philippines in 2012 [160]. The project had been in operation for twelve years at the time of publication. The island system included a 45kW PV system, inverter, and battery storage totalling 423 kWh and used by 236 households. Sustainability issues faced by the project included a total failure of the battery storage systems **[technical]** which resulted in a reduction of plant availability to only day-light hours or in some cases when there was cloud cover, total unavailability of the system. Poor components were cited as the primary cause, with equipment failing much sooner than expected. Funds for replacement were not available so the system operated with outage or very limited service for a one year period. It was found that the majority of usage was for welfare and lifestyle improvements with very few economically significant industries being provided power **[economic]**. A financial analysis showed that although the number of users has increased since inception (from around 170 in 1999), the target revenue requirement, based on the minimum needed to cover maintenance and equipment replacement over time, was never met and was regularly less than half of the requirement **[economic]**. Non-payment and late payments **[organisational]** were common over the initial years and as a response operators lowered rates and enforced a stricter payment mechanism. Unfortunately this did not prove sufficient to meet financial targets. Unsurprisingly, user response on the satisfaction of various elements of the project ranked the quantity and availability of the electricity as low **[social]**. Analysis of the management group found that it was no longer monitoring usage as the main meter had broken, was dependent on external support **[external]**, and noted the inability to institute an effective collection and fining mechanism. It was argued that management was behaving as if failure was terminal with little corrective actions possible **[organisational]**.

CIGRÉ Multi-country colloquim on rural electrification, Invernizzi, Dagbjartsson and Zomers

A 2007 colloquium by the CIGRÉ working group C6 on rural electrification captured issues of sustainability experienced by both on-grid and off-grid rural electrification efforts to date [161]. Reports were drawn from CIGRÉ working group members and provided from the perspective of Malaysia, Madagascar, South Africa, Tanzania, Ghana, Indonesia, and China. Drawbacks associated with deployment of distributed generation included: the financial in-feasibility due to low ability to pay **[economic]**, poor supply chains for replacement equipment **[external]**, limited capacity of operators **[organisational]**, poor communications infrastructure **[external]**, and variability of renewables based generation requiring additional equipment for control **[technical]**. Further learning from another colloquium later on and reported that customers of solar home systems in South Africa were unsatisfied due to low levels of service **[social]** provided and a slow repair cycle **[organisational]** [162]. Local ownership **[social]** and early involvement by the community **[social]**, sufficient training of the operators **[organisational]** are cited as helpful contributors to project performance.

Barriers to rural electrification in Mozambique and Tanzania, Ahlborg and Hammar

In a 2010 study in Mozambique and Tanzania on the drivers and barriers to rural electrification, off-grid systems were argued to be a viable solution for rural communities [163]. Although the aim of the research was on obstacles to the development of rural electrification, there were lessons relevant to the sustainability of off-grid systems. Ahlborg and Hammar interviewed 17 experts from power sector actors in the two countries with a semi-structured but broad set of questions. Off-grid systems were considered to be un-affordable without subsidies **[economic]** but are still of interest due to international donor and local political support. Additional barriers include the high administrative costs for small off-grid systems **[economic]**, and low overall capacity of solar PV systems **[organisational]**. General problems for off-grid systems are the low levels of local finances available **[external]**, limited existing capacity of locals to initiate projects **[organisational]**, logistical challenges with supplies and spare parts **[external]**, and a lack of entrepreneurship and maintenance culture. Authors found that off-grid project failure was common after only a few years.

Programmatic issues for off-grid in Nigeria, Elusakin et al.

The review by Elusakin et al. of the off-grid experience in Nigeria described it as a "monumental failure" [164, p. 53] and challenged whether further investment is warranted. Specific issues raised were the planning design inadequacies **[technical]**, corruption **[external]**, and poor quality equipment in the supply chain **[external]**. Design issues such as targeting communities which cannot afford the technology **[economic]** or do not have the capacity for management **[organisational]** of the projects resulted in abandonment. In Nigeria many of the government led off-grid projects include a diesel generator; while the upfront costs are relatively low, the ongoing costs and logistical challenge of providing the fuel supply has resulted in many failures as the economic model was unfeasible. Cases of government corruption where off-grid project funds are captured by officials and projects are announced as an election tool have impacted the reputation of the projects. The proliferation of low quality components to off-grid systems and price gouging, taking advantage of consumer ignorance, has undermined consumer trust in the industry. In response to these issues, the authors argue that projects are designed with the long-term sustainability in mind; much of their prescription is based on change in the design aspects of a project. In particular it was advocated committees should be setup to lead the planning process and supported by capable advisers (technical, funding sponsors, and community representatives), and ultimately diverging ownership from government, the status-quo. Local ownership **[social]** was considered a key element and should include proper buy-in **[social]**, and an early feasibility assessment to determine the optimal choice between off-grid and grid-extension.

Sustainability Assessment of micro-hydro in Nepal, Bhandari et al.

Bhandari et al. conduct a sustainability assessment on a 26 kW micro-hydro plant (MHP), established in 2008 in Nepal, which involved the development of locally validated sustainability indicators [165]. Indicators were organised among the main themes of social, economic, environmental, and technical with 24 sub-indicators that are weighted in consultation with the community. Data was collected primarily through interviews with 15 households, project management committee, the operator, and several external experts in alternative energy. While the authors find strong evidence that the project has had major local benefits and that many users are 'satisfied' with the power supply, several challenges were also noted. Technical issues faced were a low plant capacity factor of around 40% **[technical]**, no plans of plant upgrades **[organisational]**, and no schedule for a maintenance programme **[organisational]**. Economic sustainability was hampered by project revenue generation not sufficient to cover costs **[economic]**, limited economic benefits to local households **[economic]**, and low levels of entrepreneurial conscientiousness (local ambitions to utilise power for economic gain) **[economic]**. Additionally, the authors cited insufficient training for community members **[social]** and operators **[social]**, dependence on external expert support **[organisational]**, and difficult/potentially dangerous working conditions for operator **[social]**. Overall, the authors produced scores for each themes as follows: social 4.17 (in a scale from 1 to 5, where 5 is the highest), environmental 3.94, economic 3.74, and technical 3.04.

Challenges with micro-grid sustainability, Lepicard et al.

Lepicard et al. interview 4 micro-grids and discovered a wide range of sustainability challenges [166]. Projects faced uncertainty due to potential competition due to grid extension **[economic]**, uncertain regulatory conditions and changes **[external]**, economic model undermined by new technology and competition **[external]**, and currency risk faced by grid owners utilising external investments **[external]**. Low customer ability to pay and limited growth of demand **[economic]**, underestimation of equipment failure **[technical]** and limited design flexibility for future expansion **[technical]** were also identified. Finally recruitment, training and management of skilled field staff

[organisational] hampered the organisational health of the projects. Of several companies interviewed who were operating mini-grids, none were financially breaking even, and 3 of 4 would require double average revenues per customer to reach break even.

3.1.3 Analysis of Issues per Sustainability Category

The review of the wider experience with off-grid projects has shown that sustainability issues and obstacles to development are felt by many and are varied in their nature. In total, 156 sustainability issues were mentioned by the articles. There were organised under 84 distinct issues when the author's intended meaning was sufficiently similar. Key findings from each category is discussed in detail below as well as comparison of occurrences by project. This is followed by a general discussion of the implications for future projects and research.

The reviewed case studies do not represent an exhaustive coverage of the projects of various shapes and sizes throughout the world, but they do cover several decades and a wide geographical range. This represents the high-level themes that emerge from projects of all types – though it is recognised that a more granular classification of project types (scale, main technology, age, ecetera) could extend the current research here. The project descriptions have been purposely minimised. Instead, issues raised by the authors are highlighted so the breadth of sustainability challenges can be established.

In Figure 3.1, top economic sustainability issues are shown. The pie chart indicates proportion each particular issue was identified versus all economic issues. An unfeasible financial model was the most common issue affecting projects (considering all categories) and representing 28% of all identified economic sustainability issues. This item refers to an insufficient financial base to cover operations, maintenance and capital replacement costs. Limited ability to pay of the customers was the second most common cited economic issue (16%). Competition from the main grid (8.0%) as well as competition from new technologies (4.0%, not shown on chart) were seen together as an important sustainability challenge. An unfeasible financial model, which come up in the project design stage, was closely linked to issues that arose during the operational stage: limited ability to pay (8.0%), insufficient savings for future costs (8.0%), the lack

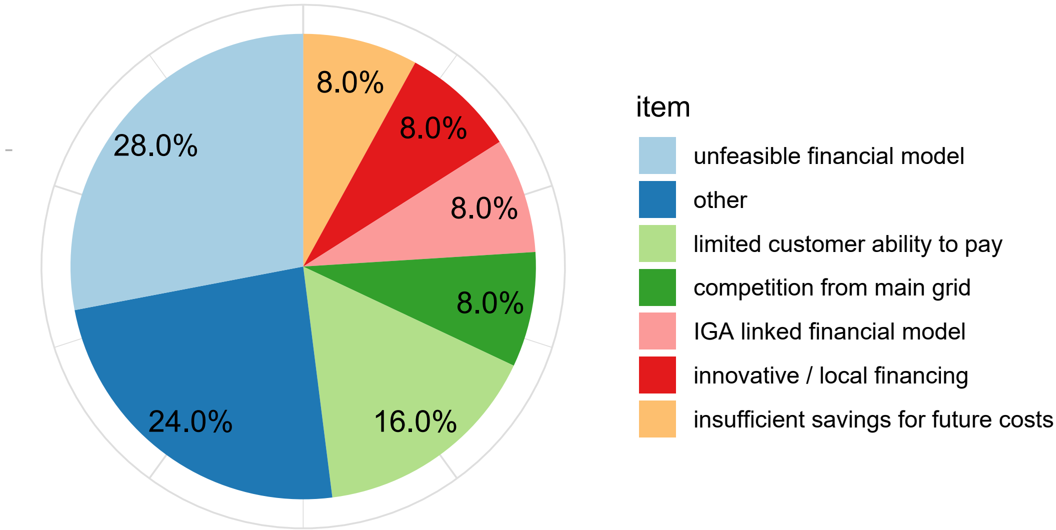

Figure 3.1: Economic Sustainability Issues

of an income generating activity (IGA) linked financial model (8.0%), and low profit margins (4.0%, not shown in chart). Two variations of financing were also mentioned: lack of innovative or local financing (8.0%) and low financing availability (4.0%, not shown).

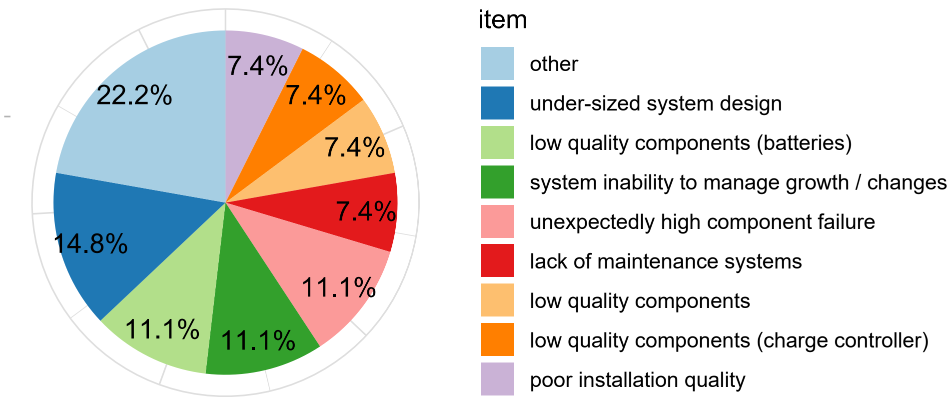

Figure 3.2: Technical Sustainability Issues

Technical sustainability issues were mentioned slightly more often than economic issues (27 times versus 25) but the range of issues was more dispersed, with distinct 15 items (see Figure 3.2). Under-sized systems was the most common issue under the category, leading to overuse and early system breakdown. Issues with failure of specific components, such as batteries or charge controllers, were tabulated separately. However, combined instances low quality of components comprised 33% of all technical issues identified (note some of these are captured in the 'other' label in the figure). Unexpectedly high component failure was perhaps a related issue (11.1%), but seems to be related to higher quality components which nonetheless did not live up to expectations. Inability to manage growth and changes to the system, including expansion and scaling, comprised 11.1% of the technical issues. Both under-designed systems (14.8%) and over-designed systems (3.7%, not shown in chart) were identified in the literature.

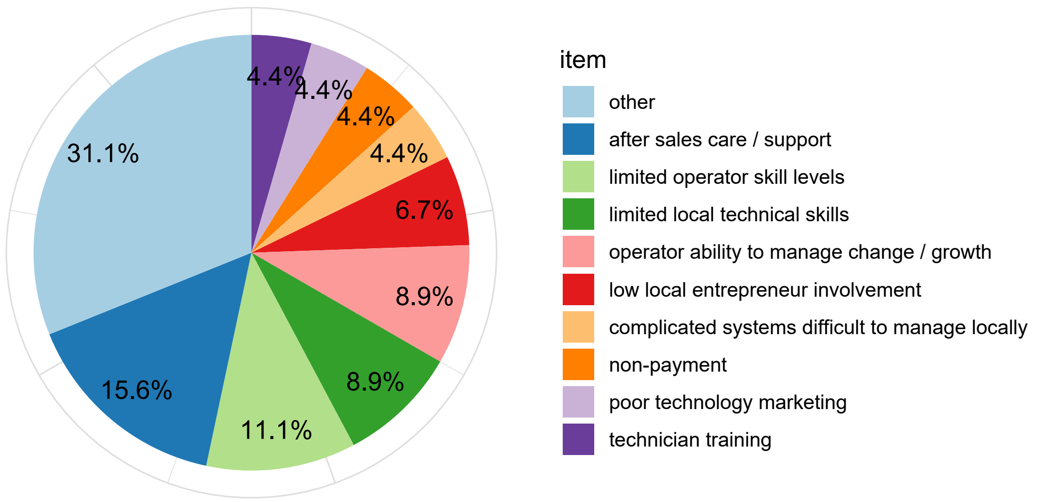

Figure 3.3: Organisational Sustainability Issues

As a category, organisational sustainability was cited the most often, with 28.2% of all mentions (44 of 156) and consisting of 22 unique sustainability issues. Lack of after sales care or support was the most common issue (15.6%) – essentially systems installed without an adequate maintenance routine setup to review and repair systems as they break-down. There were a high number (11.1%) of mentions of general lack of operator skill levels which would include issues such as business management, financial management, marketing, and specifically, technical skill shortage (8.9%). In addition to

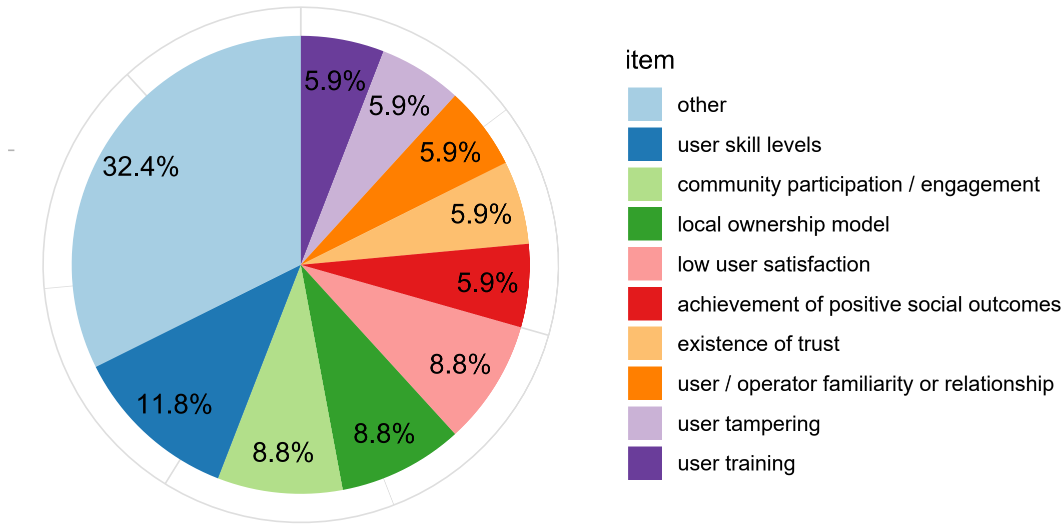

Figure 3.4: Social Sustainability Issues

skill shortages, poor routines was a culprit for sustainability: including poor customer friendly practices (2.3%, not shown), lack of a culture for auditing (2.3%, not shown), low entrepreneur involvement (6.8%), and ineffective maintenance routines (2.3%, not shown)

Social sustainability issues were the second most cited (34 of 156) behind organisational issues and had 20 unique items. The average number of mentions per social sustainability issue was 1.7 versus 2.0 for the organisational category, suggesting that the range of items was more dispersed. Low user skill levels was identified as the most common social sustainability issue (11.8%), clearly related to the existence of user training (5.9%). The delivery organisation's embeddedness in the community was captured through a number of items: the familiarity between user and operator (5.9%), lack of a local ownership model[1] (5.9%), and low community participation or engagement (8.8%). The socio-cultural context was also important with issues raised such as the project's clear achievement of positive social outcomes (5.9%), the existence of trust between the operator and community throughout the development process (5.9%).

[1]Local ownership was seen here as a positive impact.

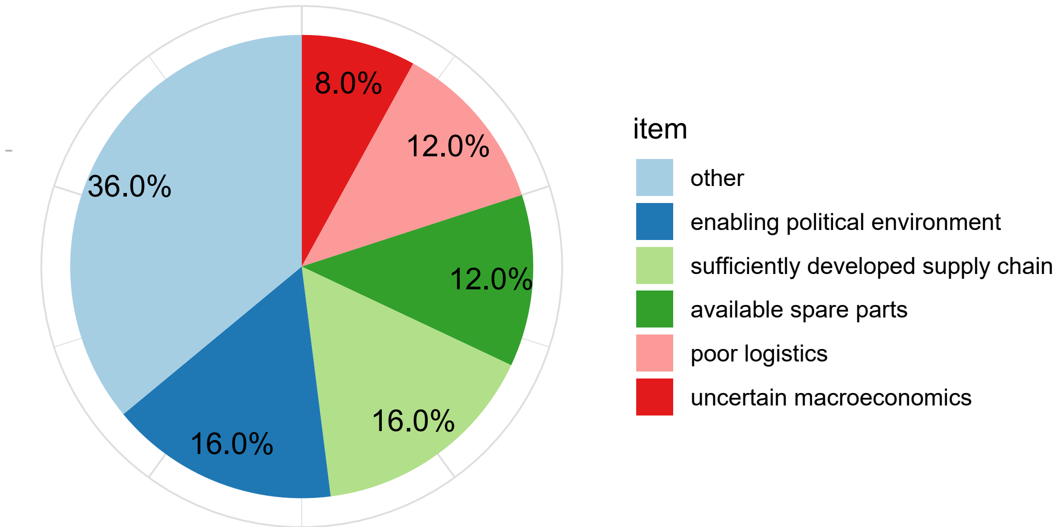

Figure 3.5: External Sustainability Issues

External sustainability issues were identified 25 times in the literature review and was comprised of 15 unique items, shown in Figure 3.5. Similar to the social category, the external category had a relatively low average number of citations per issue (1.67). Here, the major issues included the lack of existence of an enabling political environment (16.0%), an insufficiently developed supply chain (16.0%), unavailability of spare parts (12.0%) and poor logistics (12.0%). External conditions are often likened to 'gates', or, requirements for sustainability at the onset of a project. Ignoring or failing to plan ahead on how a project is meant to handle these issues has been shown by the literature to introduce serious risks.

Distribution and Concentration of Issues

The distribution and concentration of distinct issues provides an insight into how authors understand sustainability. The distribution of distinct sustainability items that were identified per article is shown in Figure 3.6 as a density plot, which is similar in function to a histogram, but does not use bins and instead uses a Gaussian kernel density estimate to produce a continuous curve. The mean is shown as the dashed vertical line and corresponds to 7.48 issues per article. The maximum issues identified by a single article was 12 [159]. The low overall average is perhaps a surprising result, given

84 unique issues were found by all the authors. The relatively low coverage of issues per study, which were primarily aimed at evaluating and assessing project sustainability, is perhaps an indication that there is diverging understanding of sustainability in practice and reinforces the motivation of the research presented in this thesis.

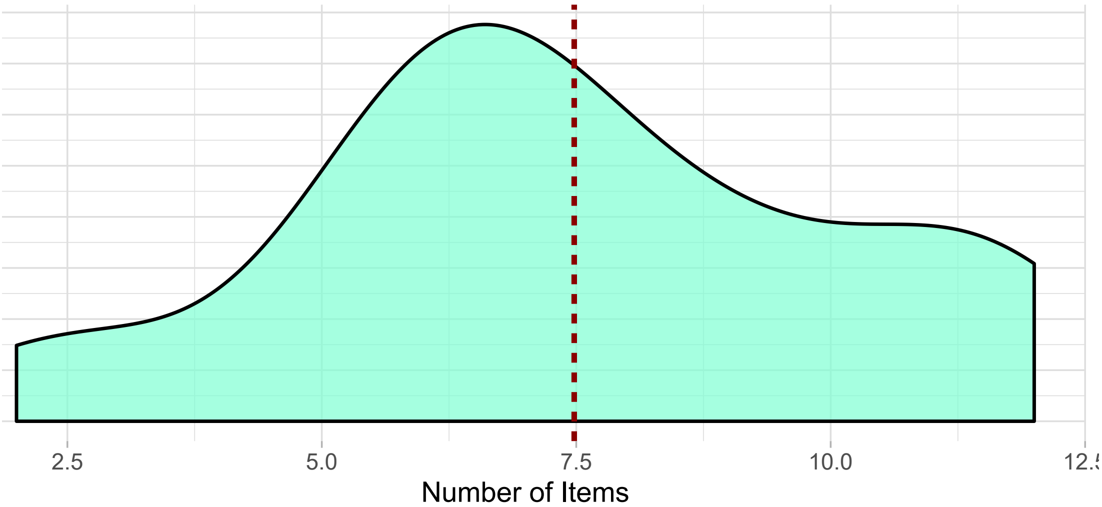

Figure 3.6: Distribution of distinct sustainability issues identified per article

As described earlier in this Chapter, issues have been counted and classified under the sustainability categories for each article. It can be observed that within each article the authors do not identify the same specific sustainability issues, quantity of issues, and proportion of issues under each sustainability category. In some case, the focus of their evaluation is weighted significantly onto one category versus than others. Is this inconsistency important? If each article were to focus solely on a single category (to exaggerate the point), what would this suggest about the practical understanding of the components of sustainability?

To explore these questions the remainder of this section utilises a metric developed here, "concentration", that represents the proportion one category is favoured per each article versus other categories. To interpret the metric, consider an article which identified one issue under each category; it would have a value of 16.6% for each category for this article[2]. Conversely, an article which only identified issues among the organisa-

[2]Specifically: since there are six categories, 6 issues would have been found, and therefore $1/6*100 = 16.6\%$

tional category, and no other issues, would have a point at 100% on the organisational column and a point at 0% for the other issues.

In Figure 3.7, the concentration in each category for a given article versus the total issues mentioned by that article is plotted once under each main category[3]. The box and whiskers plot visualise the distribution of this metric – the mid point of each box is the median, the upper and lower bounds of the box are the 75th and 25th percentile and the whiskers extend the box length by 1.5x in either direction.

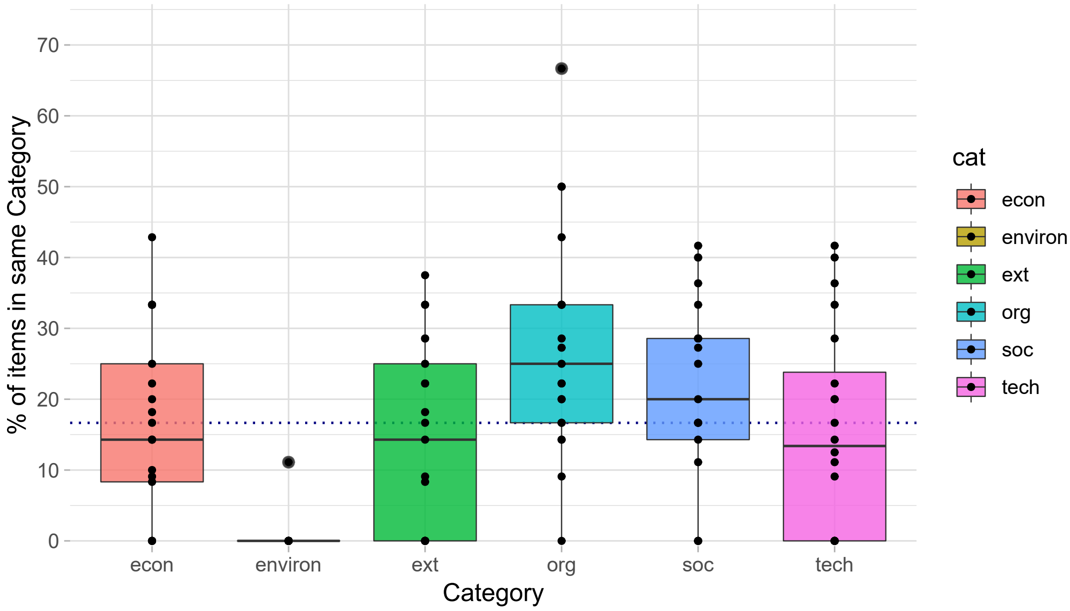

Figure 3.7: Concentration of Cited Sustainability Issues per Article

While many projects may be premised on achieving environmentally friendly outcomes, it is striking that the median concentration of the environmental category is zero; it simply was not an issue for most projects. Concentration of external and technical issues are similar and both have a median of just under 15%. However, as the 25% percentile of the distribution is at zero, this indicates a significant bunching of projects which found no external or technical issues whatsoever. The distribution of economic issue concentration, in contrast, had a more narrow range with quartiles between 25% and 8.5%. Only 5 articles failed to identify an economic sustainability issue. The remaining articles generally did not concentrate solely on economic issues.

[3]Therefore, each article appears once in each sustainability column

Both distributions for technical and external concentrations had a larger proportion of more concentrated focii than the economic concentration.

The social and organisational concentrations both exhibited relatively higher concentration than other categories. The median for social concentration was 20%; it was 25% for organisational concentration. For both categories, very few articles failed to identify an issue in these categories. However, the remaining articles tended to concentrate more heavily under these category, respectively.

Given the ambiguity in which the term 'sustainability' is understood and applied to projects, it may be no surprise that the literature review has found higher concentrations under one category or another. The distribution of concentration is shown in Figure 3.8 – the colours reflect the sustainability categories. Roughly 150 observations of concentrations are shown here, one for each article and each category. Since there is little justification on the 'correct' level of concentration per category, it seems reasonable to make the assumption that wider band around 16.6% is acceptable. The dashed lines on the curve are set at ±8% over the naive expected concentration of 16.6%. With only 31.7% of concentrations falling within this range, it suggests that evaluations of many projects are indeed more concentrated on individual categories. This conclusion is consistent with 35.7% of concentrations being 0% concentration – these represent gaps in the article where issues under the category are not identified.

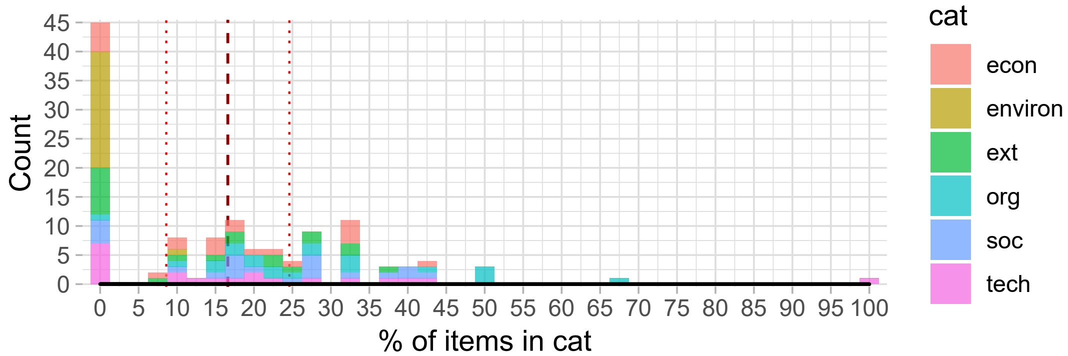

Figure 3.8: Distribution of concentration of sustainability issues

This analysis has captured the breadth of sustainability issues documented within the literature for off-grid electrical projects in developing countries. In total 156 issues were identified by the articles and represented as 84 unique sustainability items. These were classified under the main categories including economic, social, technical, environmental, organisational, and external. A method to represent the concentration of issues under each category was proposed and used to analyse the coverage under each category and by article. There was a surprisingly high level of concentration under the organisational category (median of 25%) as well as gaps in each category, but particularly under environmental, external, and technical. The analysis suggests that there is ambiguity in the understanding of the term sustainability, evidenced by the inconsistent concentration levels and existence of gaps, when used in practice for evaluations and assessments.

3.2 Case Studies of Individual Project Sustainability

This section documents three case studies from the authors personal experience involving sustainability of off-grid electrical projects in developing countries. The first case study is in Malawi and captures the results of a country-wide sustainability evaluation around the Malawi Renewable Energy Acceleration Programme (MREAP). The second case study takes place in Kenya at a wind-solar hybrid micro-grid at the Muhuru Bay. This captures a snapshot of the project operations during a transitional period after the lead operator left the project following an instance of theft. The third case study documents the sustainability challenges faced by the University of Strathclyde Gambia Project. It highlights the external dependency issues, interrelationship between the perception of positive community outcomes and project revenues, and challenges with financial sustainability. These case studies serve as additional direct evidence of project sustainability levels, but more importantly, tell a richer narrative of how projects struggle to maintain sustainability. For clarity, the key insights from each case study are provided at the beginning their respective sub-section.

3.2.1 Malawi Renewable Energy Acceleration Programme

The Malawi Renewable Energy Acceleration Programme (MREAP) is an integrated energy development programme funded by the Scottish Government and running from

2012-2015 in Malawi [167]. The programme incorporated several complementary strands of work including community energy development, institutional support, renewable energy capacity building, and a wind potential study. The programme is important first as this thesis draws primary data from the projects involved in MREAP. Second, several dedicated studies were undertaken within the programme are reviewed here as a case study to learn about sustainability issues for off-grid energy projects.

Key Insights from Case Study

- A 2012 scoping study of rural solar PV projects found a legacy of sustainability challenges including battery failures, insufficient income to support the project, failed equipment, undersized systems, poor project siting, low managerial and technical support skills, insufficient user training, lack of long-term maintenance contracts, lack of community ownership of projects, and misuse of project generated funds.
- In 2016 a country wide comprehensive sustainability survey involving metrics from 4 sustainability factors and targeting solar PV projects at public facilities found that no projects were found to be 'fully sustainable'. Only 2 projects received an overall score of 0.5 or higher (1.0 was considered a maximum).
- Refinements from the MREAP model contributed to generally improved sustainability prospects. This involved increasing community agency in design and procurement of projects, closely aligning project objectives to expressed community needs, added training for local organisations running the project,and requiring certification with the MERA, the national regulatory agency.
- The infeasibility of the project economic model was the most significant single weakness - almost all projects had far too little income to support the long-term capital replacements costs. Projects faced particularly low scores in the following metrics: Community contributions, stakeholder meeting frequency (about projects), initial technical training, all types of ongoing training, and existence of a formal project bank account. For the technical sustainability, the majority of projects undersized the batteries and panel and on average projects could only

provide for roughly 60% of electrical energy needs.

- The community energy model in Malawi has been trialed whereby the community is expected to develop, own, operate, maintain, and potentially expand an off-grid solar PV project. That model stretched the limits of the communities capability to sustainably manage the project. The MREAP projects resulted in clearly positive impacts to the community and improved the sustainability prospects. However, it came at the a significant investment: time, money, local development and external technical support, which may yet prove difficult to maintain in the long-term.

Programme and Project Description

As a development programme, a major objective of MREAP was to develop new community-based energy projects in areas currently without access to electricity. On this level the project was successful: upon its conclusion in March 2015, 46 new off-grid community energy projects had been implemented and 4 'Strategic Energy Projects' were similarly supported as learning cases [168]. The programme was estimated to have improved access to energy for nearly 80,000 rural Malawians, many gaining their first access to a clean lighting source. Technologies included in these projects included solar PV institutional systems on primary schools (see Figure 3.9, Source: Peter Dauenhauer), secondary schools, health centres, community buildings, teacher training facilities, solar home systems, and pico solar products. Non-solar technologies were a micro-hydro mini-grid, 12 biogas digesters, a regional improved cook-stove project, and a forest management programme.

The development approach implemented for the projects was based on adoption of best practice from development practitioners in the country including academia (comprised of Mzuzu University and the University of Malawi Polytechnic), a local NGO with international presence (Concern Universal, later renamed to United Purpose), and a local development organisation (Mulanje Renewable Energy Agency). These organisations consisted of the implementers of each of the 4 Strategic Energy Project (SEPs). The southern-most SEP deployed in Chikwawa district was distinct as it deployed rural

Figure 3.9: An MREAP Solar PV Project in Malawi – Ndakwera Primary School

off-grid solar photovoltaic systems at primary schools and health centres but also included a data acquisition system and a technical design led by WASHTED, a centre at the University of Malawi Polytechnic. The development approach was supported by international partners including the University of Strathclyde, IOD PARC a development consultancy, and Community Energy Scotland (CES). The model shared similar aspects to the CES development approach implemented in Scotland over the previous decade. The specifics of the method are described in the following sections.

Country-wide Sustainability Challenges Prior to MREAP

Prior to the implementation of MREAP, a scoping study was undertaken by IOD PARC to study high profile cases of community energy. The resulting evaluation of 12 case studies found many sustainability issues at play: battery failures (technical), insufficient income to support operations (economic), failed equipment (technical), undersized systems (technical), poor renewable energy technology selection and project siting (technical), limited support from local management agencies (organisational), low management and technical support skills (organisational), and unforeseen competition (economic) [169]. Further findings from the evaluation included more issues: insufficient user training on system usage (social), lack of long-term maintenance contracts (organisational), lack of community ownership over the projects (social), insufficient training for managing entity (organisational) or users (social), misuse of generated funds/corruption (social and organisational), potential for theft of equipment (social) [170].

The overall lack of sustainability and limited evidence base made a strong case for MREAP to generate more robust learning on how to create more sustainable community energy models in Malawi.

The Community Energy Model from MREAP

In the context of the failed past projects, MREAP sought to improve the development approach for new projects. These had a number of distinctive features. First, the entry point for the project were community based organisations (CBOs) which drew from representatives of the community and were a permanent structure, already in place, and sure to exist even without external support. Second, local needs were assessed and used to self-determine, with assistance of a development officer, the distinct type of project that would advance and be developed. This resulted in high level of relevance to the expressed local needs and strong community ownership. Third, communities were targeted that had high poverty indicators. This occurred in two stages; at first, districts that on aggregate were relatively impoverished were identified, and then again at the community level within the district. As a result, the projects targeted some of the poorest areas which were often the most remote and hardest to reach. Fourth, the technical deployment improved on the previous iterations in the country, namely, all installations were certified by the Malawi Energy Regulatory Authority (MERA), a step which was only inconsistent previously. Finally, all projects developed customised business plans, with close involvement by the community in their design, that would utilise energy production (or products) to generate an income in support of the project.

A year following the completion of the programme, in 2016, two evaluations of nationwide off-grid community based solar PV project sustainability were conducted covering all of the MREAP projects and totalling 65 projects overall [171, 172]. The studies aimed capturing quantitative and qualitative evidence to determine the level of sustainability of the community energy in Malawi. The customised survey covered the following sustainability categories: economics, social, technical, and organisational. Indicators were developed, based on the existing literature sources but were also justified so that they were directly related to perceived project related issues.

Dauenhauer et al found major sustainability challenges within each category and no single project could be considered fully sustainable [172, 173]. The method equally weighted sub-metrics under each category, the results of which are shown in Figure (3.10, Source: [173]), where the MREAP projects are labelled as 'CEDP' and 'SEP' (two subsets of MREAP projects) in blue and green. After the scores were normalised from 0 to 1, only two projects (both CEDP) scored consistently over 0.5 on each category. The lowest overall score, for all projects, was in the economic sustainability category, where most projects simply had far too little income to support the long-term capital replacement expenses that would occur as components of the system failed. MREAP systems fared better than other systems, likely due to the emphasis on establishing income generating activities.

Overall, the study found that SEP and CEDP projects had a higher average mean score than the other projects. SEP projects had higher technical scores, primarily due to consistently more conservative system sizing. CEDP projects had generally higher performance on other measures. Although the qualitative study preceded the quantitative effort, Dauenhauer and Frame argue that the community energy model in

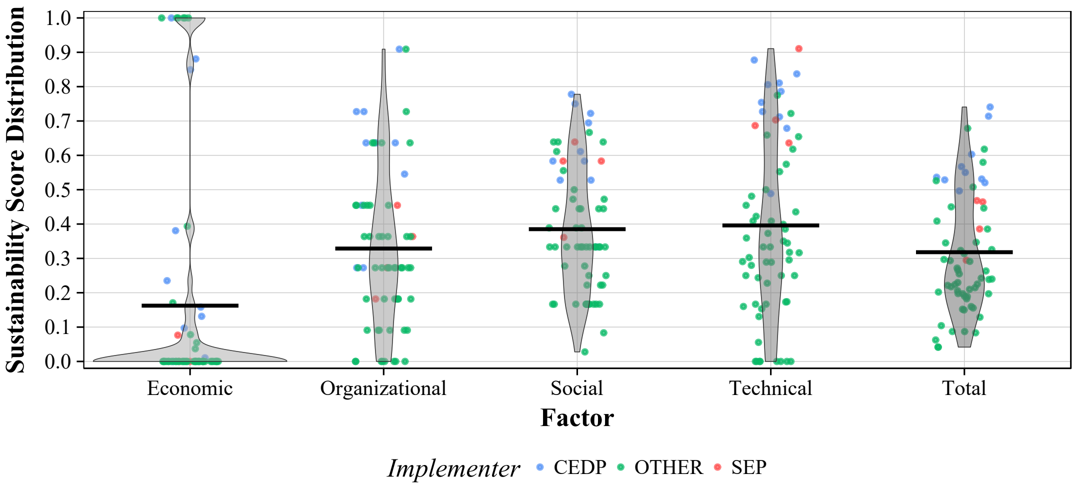

Figure 3.10: MREAP Sustainability Scores by Category

Malawi has been remarkably capable for positively impacting the communities [171]. However, the extent of the community capacity to sustain a project was seemingly at its limit. As was described, considerable effort – time, money, local development and external technical support – was needed to establish the MREAP projects with a good prospect for sustainability. The study result after several years of operation seem to suggest this investment did indeed have an impact on the sustainability prospects of the projects but the ability to replicate, scale, and maintain ongoing support remains to be seen. Given the overall scores, the authors note that further refinement of the model, especially by developing stronger financial performance of the projects, is needed to achieve acceptable sustainability levels.

3.2.2 Kilowatts for Humanity Muhuru Bay Micro Grid Project

This section describes the sustainability experience of the Muhuru Bay Micro Grid in Kenya. As a volunteer for the NGO Kilowatts for Humanity in Seattle, USA, and ongoing research collaboration this author was aware of the design decisions and was invited post-installation to address the business sustainability issues which were being observed by the team. Data from this is primarily sourced from personal notes and internal reporting to the implementing organisation.

Key Insights from Case Study

- A solar wind hybrid project installed in Muhuru Bay Kenya experienced sustainability challenges shortly after the Seattle-based installation team left. An incident of theft and subsequent disappearance of the local operator were the initial causes for unsustainability.
- Operational aspects of rural off-grid projects that are also businesses were became difficult to maintain. Following the theft, there was vacuum of skills which included basic charging management, customer management, sales and marketing, financial accounting, and managing competition.
- The inter-relatedness and complexity of the relationships between different sustainability factors was demonstrated. A lack of skills led to lowered utilisation of the resources and lowered financial performance. Shady business practices by the outgoing operator undermined the customer's trust in the business resulting in non-payment. Additionally, the sequence of events was important, initial problems snowballed into the next.
- Adaptability of the project owner was concluded to be the most important single aspect of the project's future sustainability.
- The dynamic relationship of sustainability issues over time shown in the project suggest that the 'spot check' method, where conclusions are based on measurements at a single point in time, for sustainability evaluations may be insufficient to capture the root causes.
- The sustainability planning during the project design stage overlooked a number of the potential issues that manifested in the project: owner training needs, ownership arrangement, handling competition, and responding to theft. Project modelling for Muhuru Bay was heavily dependent on techno-economic designs. This weakness was recognised by the implementing organisation, though robust modelling tools do not exist.

Project Overview

The Muhuru Bay Micro Grid project at Kristy's Cape Academy in Kenya was completed in 2014 by a consortium of volunteers from Seattle University, IEEE Smart Village, and an NGO now known as Kilowatts for Humanity (KWH) [174]. The project was installed in August 2014 and was a 3 KW hybrid wind and solar project with a portable battery charging station and was connected to several local households (see Figure 3.11, source Peter Dauenhauer). The project was housed in a purpose built structure by KWH and referred to as a kiosk.

Figure 3.11: Muhuru Bay Micro Grid Turbines and Solar Panels

A sustainable business model was planned – the design included income generating activities: portable battery kit charging, mobile phone charging, sale of cold drinks, and sale of foodstuffs. The business model assumptions were based on a community consultation held to determine willingness to pay for various services that could be provided and to address needs expressed by the community [175]. Product pricing assumed that the customer's existing energy expenditure could be spent on the kiosk products. A significant portion of the business capital was pre-invested by the implementing organisation in BBOXX [62] home lighting kits. Customers were expected to pay a small upfront registration fee and then monthly payments to continue to access the home kits.

The forecasted cash flow was sufficient to cover the maintenance and replacement costs for all major components over a 10-year term. A training team worked with the locally selected kiosk operator and covered a relatively broad range of subjects: equipment maintenance, day-to-day operations, and the implications of the financial model.

Initial Sustainability Issues - Theft and Loss of Skills

Throughout the narrative that follows, the sustainability issues can be referenced in the flow diagram as shown in Figure 3.12. Assumptions that were missed or overlooked by the implementing organisation are shown by the dashed lines. Major sustainability issues are given a heavier outline.

Shortly after the installation team left there were some worrisome signs that the new business was having problems. The owner informed the implementation team that the operator running the kiosk had been stealing some of the money, though the extent was not entirely clear. Furthermore, upon confronting the operator, he had fled the village and had not returned.

This prompted a follow-up visit 4 months after installation, whereby it was intended to learn more about the details of the incident and suggest corrective actions that were appropriate. In December 2014, a two person research team involving Dr Henry Louie (Seattle University) and Peter Dauenhauer (University of Strathclyde) were dispatched to assess the technical and economic health of the project over the course of one week in the country.

Upon investigation, the monetary theft was small but substantial for the new busi-

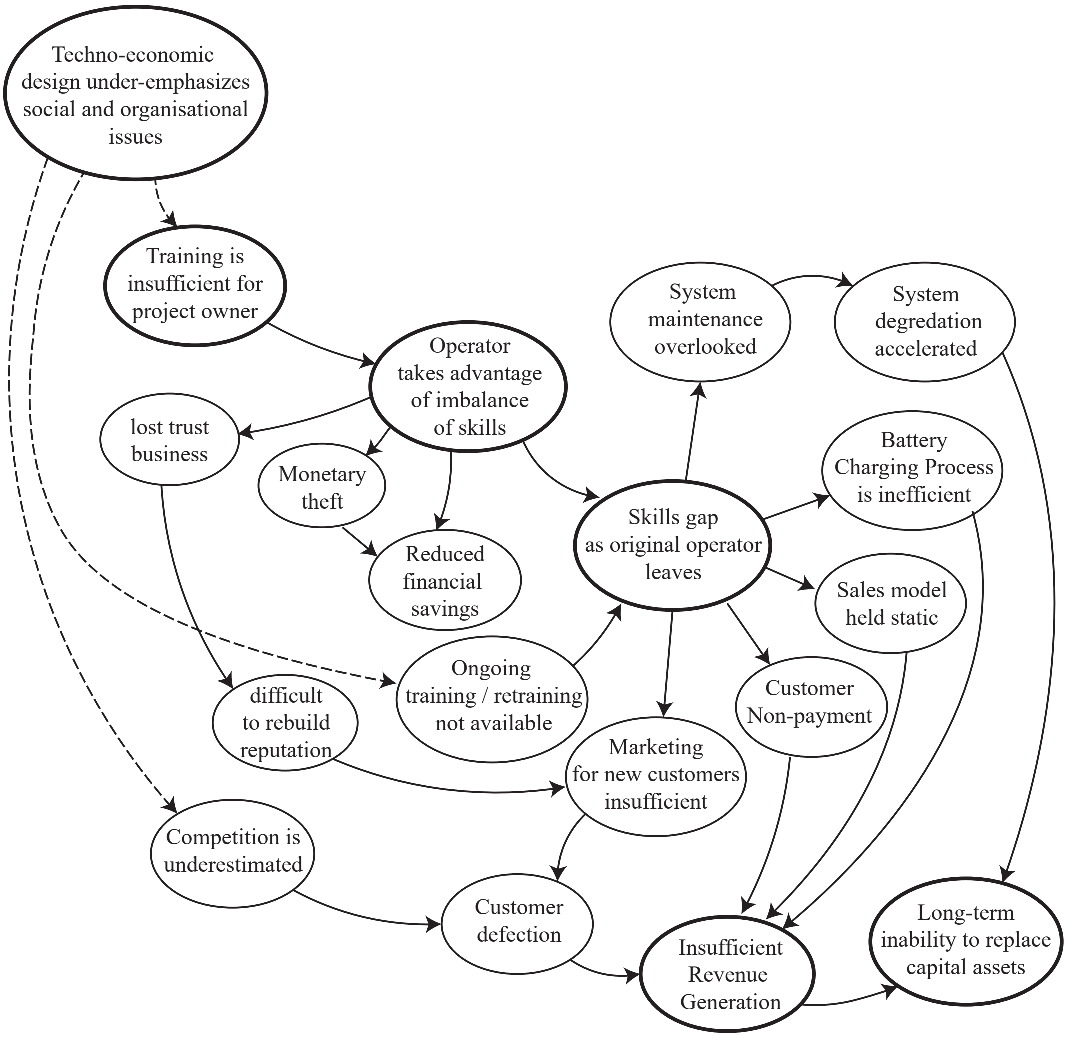

Figure 3.12: Interrelatedness of sustainability issues at the Muhuru Bay Micro Grid

ness operation: 17,000 KES (or $188 USD)[4]. After auditing the daily transactions and stocks, it became clear that the operator had under-reported the income on the monitoring sheets kept for the project. He had three tactics to steal from the business.

First, monthly service payments were made at the customers' homes, out of view of the owner, and some portion of these were pocketed. Second, part of the lighting kits were sold at an overly marked down price or given away free, in order to incentivise customers who would then pay a registration fee. Third, registration fees were all pocketed by the operator. Fourth, a portion of the revenues from mobile phone charging was also missing. This left the project's balance sheet in a dire position; the original savings goal was for around 53,000 KES saved per month. However, beyond the immediate financial loss, the theft was felt more widely for the business as it coped with customer relationships and a loss of skills to run the project.

Secondary sustainability issues

The **business credibility was damaged** from both the operators actions and the hasty transition following his departure. Several critical procedural steps were skipped including signing of contracts with customers, the handing out of goods which weren't meant to be free, and the lack of enforcement on late payment. When the kiosk owner stepped into operating the business, customer contracts needed to be re-established after the fact and correct the ambiguity left in terms by the original operator. In many cases, customers were already in breach of the contractual conditions, late in their payments or in arrears. Although it is difficult to know precisely the effect on customer satisfaction and confidence in the business, this was surely damaged through this process.

The issue of **non-payment** came to head after the operator left. By the end of November, nearly every customer was behind in their payments and some customers by almost 3 months, on average 1.5 months of payment was due per customer, leaving KES 102,290 outstanding. Poor record keeping by the operator meant that there was uncertainty on how much of this might have been paid by the customers but not repor-

[4]using 27 Nov 2014 exchange rate of KES 90 = 1 USD

ted properly. There was no 'good' solution. The operator's undisciplined handling of the customer payments had created a culture where non- or late- payment was acceptable. Enforcing the contract once this culture was established was required confiscation of the equipment until payment occurred (see Figure 3.13, source Peter Dauenhauer). Although this was the chosen approach, it severely hampered revenues while the equipment was collected and then returned to service with a proper contractual setup. For some customers, there would be a real question of the value of making the overdue payment to regain access to the kiosk services. This raised the attractiveness of alternatives that were available from competitors.

In addition, the kiosk had an immediate problem with a **skill shortage** in keeping the normal activities running smoothly. The original operator was the only recipient of training provisions during project installation. The project owner, who took over operations, lacked sufficient skills to keep operate the kiosk efficiently. Technical activities such as normal maintenance (cleaning solar panels, equipment inspection, battery fluid replacement, etc.), managing the charging cycle of the home battery kits, and troubleshooting of the various components were understood only at a superficial level. Despite their dedication, the owners struggled with managing the day-to-day the business activities such as handling payments, managing employees, customer service, marketing, and even ensuring a consistent business opening and close out schedule. In retrospect, the imbalanced level training went to the original operator versus the owners which poorly prepared the owner to step in when needed. Furthermore it allowed the operator to take advantage of his knowledge of the system to hide his actions from the owners.

In the months after the system installation, **competition accelerated** in the local village. This came in the form of small renewable products and distributed through the popular M-Kopa Solar programme [176]. The advantages of this programme included the use well received products (manufactured by d.light) combined with a mobile payment scheme (MPesa) and a rent-to-own model. The kiosk employed a monthly rental service and customers had started complaining. The system could be bought in very small increments, daily, and could therefore lower the incremental costs when com-

Figure 3.13: Home Lighting Kits Withheld for non-payment

pared to the kiosk products which required monthly payments. Although a survey was completed prior to the project installation, this form of competition was not identified and appeared to be a recent occurrence. There were several responses which were considered by the owner in consultation with the research team: adjust the marketing approach, adjust the pricing scheme, or adjust the payment model.

Post-evaluation status of project

In the months following the field visit, the owners hired a new operator and took on a greater role in the day-to-day operations. Nearly all of the home battery kits had to be withheld and new contracts set. Despite the need for income the owner did not aggressively market the kits and the majority were instead sat unproductively at the kiosk.

The monthly price for the kits was significantly reduced to 50% of initial price to better compete, although this would obviously hamper the revenue generation. It was estimated that if the owners were able to save an additional KES 20,000 for three months following the field visit, then they could get back on track with the savings payments needed for maintenance and replacement of the equipment.

During the field visit the owner had already started experimenting with setting up different lines of business. A refrigerator was purchased so more cold drink stocks could be held and some baked goods were providing an important stream of income. In 2017, the implementing organisation helped the kiosk setup an ice-making business which could also be used to cool fish from the nearby lake and thereby support this market.

Following the incident several follow-up visits to the project found that that station batteries had not been maintained properly by the owner, despite manuals and some training. By 2019, it became clear that these had degraded completely and were not providing the functionality that was originally planned. Furthermore, the grid had at last arrived at Muhuru Bay prompting the owner and implementing organisation to decommission the project. While the project has had a positive impact to the community during its years of operation, the incoming grid connection and existence of agile competition suggests that continued operation would not have been possible in any case.

Conclusions

The narrative of the Muhuru Bay Micro-grid experience provides a compelling perspective of the dynamics of a rural electric service business operating and facing the real sustainability challenges. The project design, training, and business model assumptions seemed to provide a reasonable level of sustainability at the onset of the project. The project designers did not expect the challenge of transition needed following the theft and departure of the original operator. During the design, it was not envisioned that within the first year of operation a complete retraining would be needed, a serious competitor would emerge almost immediately, the business reputation in the community would be tarnished, or that it would face a serious incident of theft. Yet, these are the realities of operation in many remote communities.

Several insights about sustainability can be drawn from Muhuru Bay. First, it demonstrated the inter-relatedness of many factors in project sustainability. The sequence that these factors occurred was important as one problem snowballed into next.

The issues spanned many related factors: social (customer's perceptions and expectations), organisational (training need, business routines which were undermined) and economic (financial non-performance). Additionally, the factors had a dynamic relationship – for example, once the original operator left, it only then became an issue that the owner did not have the skills needed to maintain the system. The loss of trust in the business due to the ambiguity of customer contracts made it difficult to rebuild the reputation financial performance and raise the (relative) attractiveness of alternatives.

Second, the nature and process of conducting sustainability evaluations can be informed by this experience. A spot check during a short window of time with an 'expert' evaluator using the current conditions as evidence may be insufficient to forecast future sustainability. In retrospect and in face of the challenges experienced, it was the adaptability of the project, owner, and support team (or lack thereof) to respond to the situation which was the most important aspect of its sustainability. The current conditions were not the full picture and underestimated the changes that were underway. The result of the evaluation, before and after the theft, would have led to clearly different conclusions, basing these only on the conditions at the given time. On the spot metrics are clearly important, yet the project experience suggests that their use in evaluations cannot dominate the conclusions. Dynamic considerations must also be considered.

Third, the impact of various scenarios which could affect the project at the design stage were not fully understood or modelled. It is with the benefit of hindsight that these issues are more easily identified, but the training need for the owners, ownership arrangement, the introduction competition to the core business, and indeed theft by the operator may have been a more central part of the project design. This oversight is not unusual —- planning for and modelling every major contingency is potentially time consuming, costly and erroneous. The method used weighs heavily on techno-economic system design optimisation that determines the best technology choice for a given project within highly restrictive socio-economic and organisational context. In this case study these tools could handle the critical issues Muhuru Bay faced: increasing competition, theft, retaining, business model re-design once regular operations had begun. Assumptions on these complex issues take the place of robust modelling which could occur.

With the critique on the design process in mind, a second related point is how the learning from the experience goes on to affect the future design process. In future projects, an improved approach, primed by the experience in Muhuru Bay, has emerged at KWH, where the ownership structure, transparency, backup operators, more serious consideration of diverse businesses, are all considered. Little to no literature exists that discusses the learning process around these design iterations that build on successive field experiences and result in changes to the process and tools that are used.

3.2.3 University of Strathclyde Gambia Project

This section describes the sustainability experience of the University of Strathclyde Gambia Project. The programme is a charitable effort led by the University and has involved students and academic staff installing off-grid photovoltaic systems. Installations have been occurred roughly every other year since inception and the programme has gone to to install seven solar PV based projects up to 2014. Data from this is primarily sourced from personal notes during a 2014 visit where the author of this thesis was responsible for the supervision of several undergraduate students conducting research on the sustainability of business models associated with these projects. The research methods involved system inspection, interviews with project owners, interviews with users, and a review of financial records.

Key Insights from Case Study

- Seven off-grid solar PV projects at rural schools from the University of Strathclyde Gambia Project provided basic access to rural lighting but face several critical sustainability challenges due to the dispersed decision-making arrangement and insufficient local revenue generation.
- Technical capacity of the operators was found to be lacking at all locations. Attempted local repairs have left one of the systems at risk of damage to the station batteries.

- Revenue generation at the projects was far below what was needed to replace long-term asset replacement. The majority of the income was spent on the support of school-related expenses. A free mobile phone charging scheme was provided for the educators.
- The University's obligation for repair and replacement costs for the projects represents a significant technical and economic dependency for the projects. Technically, the yearly field visits exposes the projects to potentially long periods of down time should a fault occur, as was demonstrated by one of the projects. A lack of local technical skills suggests that this arrangement is the most practical for the short-term, but more sustainable long-term options should be explored such as training or developing a relationship a local organisation which can respond quickly.
- Options for building up the projects' economic feasibility will be an ongoing challenge. Sourcing local parts for future replacement in order to build a financial model are a first step. The local project operators may have a steep learning curve to overcome in order to successfully fund and procure a one-to-one replacement of parts. Nevertheless, a more disciplined management of energy utilisation for commercial purposes, for boosting revenues, as well as expense management, to boost savings, must be implemented. Unfortunately, the complex relationship between the community expectation for free public-benefiting goods suggests this may not be possible without undermining the social contract with the community.
- The field visit revealed an complex relationship between the project and community. The community's support for the project, namely the willingness to patronise the mobile phone charging scheme was dependent, in part, on the project's ability to provide free public-benefits.

Project Overview

All 7 Solar PV based off-grid projects have been installed under the programme were completed by University staff and using materials sourced in the UK and shipped to the Gambia. The systems were small – with PV arrays around 360 Watts, basic inverters, and 12-volt sealed lead acid batteries providing roughly 2.4kWh of energy storage.

The ownership model for each project emerged organically and from the University's handling of funding, procurement, installation and an ongoing desire to it remain connected and supportive of the projects. Locally, the School Management Committee (SMC), consisting of school staff and parents, handled all decisions relating to day-to-day management of the project. On an ongoing basis, the University has remained a critical support for projects when repairs are needed. Decision making responsibilities were split between community, leadership persons within the schools, and the University of Strathclyde staff.

Each project provided basic but critical access to power at primary schools that do not have access to the main grid. The projects have provided free basic lighting in one or more school blocks, free mobile phone charging for staff, and a source of income used for various local public projects. The income was generated from local non-staff customers who charged their mobile phones at the charge point. The projects were intended as community-based which meant, in practice, that there was an expectation for providing a free community good.

The University staff holds an advisory role to the projects during their periodic visits, but has little oversight into the financial management of any generated revenues. Maintenance and repair responsibilities were handled by the University who also bore the financial obligation.

Technical State of the Projects

System usage data from a prototype data logger at the Kudang project provides some granular information on the **technical functionality** of the projects [177]. Over a period from December 13, 2013 to February 18, 2014 around 7,500 performance measurements were taken on the panel voltage, battery voltage, charging current, and load current.

Figure 3.14: Solar PV Project at Sambel Kunda, The Gambia

Time series technical data is plotted in Figure 3.15. During daytime hours, the charging current is maximised and the battery and panel voltages are nearly identical. Battery voltage ranged between 11.36 to 13.09 V (12V nominal system). The two main loads on the system were mobile phone charging and a lighting load at night when pupils were studying. From the daily load and generation profile shown in Figure 3.16 it is apparent that the average system daily load peak was is at 20:00 at 60W. Average Watts are plotted as a solid curve, while the maximum Watts are dashed. The maximum peak load was observed at 11:15 AM at 115W. Energy use was heaviest from 18:45 to 22:45 as mobile phones were charged concurrently with night-time study. A significant proportion of energy use was during day time hours between 10:00 and 18:45. Late evening and early morning is characterised by a light load that trails off from 22:35 to 5:00 AM, likely mobile phone charging. Hours 6:00 to 8:00 AM had virtually no load.

A daily average profile of the battery and panel voltages are shown in Figure 3.17. A profile of the daily charging and load current is shown in Figure 3.18. The profiles are consistent with a system that is fully utilised. The charging current over the daytime hours indicates that all of the available potential energy (minus losses) is being generated and consumed either by load or by charging the battery. Over this time window, the battery and panel voltage are closely aligned. Since a significant proportion of the energy consumption is non-coincidental with peak charging, energy storage is critical to meet usage expectations. For the most part, battery voltage levels, a rough estimate of the state of charge, are healthy with a minimum of 11.36 V. Close inspection of the full time-series indicates no discernible low-voltage disconnects by the charge controller. However, over the entire time series the battery voltage only reached 13 V or higher on 12 instances (of 15 minute increments) which suggests that the system is not fully charging or able to achieve the boost charge[5] needed for good battery health.

Over the entire period, the non-coincidence of load to generation can be comparing by calculating net energy consumed or generated over the two time periods: hours 0 - 9 and 20 - 23, the hours without solar generation (off-peak), and hours 10 - 19 where solar generation is present (on-peak). Average daily net energy over these periods was 411 Wh during solar generation, and -248 Wh during non-generation hours, or a ratio of 60% off-peak to on-peak net energy. Supplying load by the battery storage will also be less efficient than directly by the panel, typically in the 80% - 90% range. Reducing night time loads by load shifting, or reducing overall loads, is needed to provide ample charging opportunities for the charge controller to provide boost charges.

[5]Typically charge controllers are designed to periodically allow the solar panels to increase the voltage higher than would normally be allowed under its protection. This ‘boost charge’ is decreases battery sulfation and failure to do so reduces the battery’s ability to hold a charge.

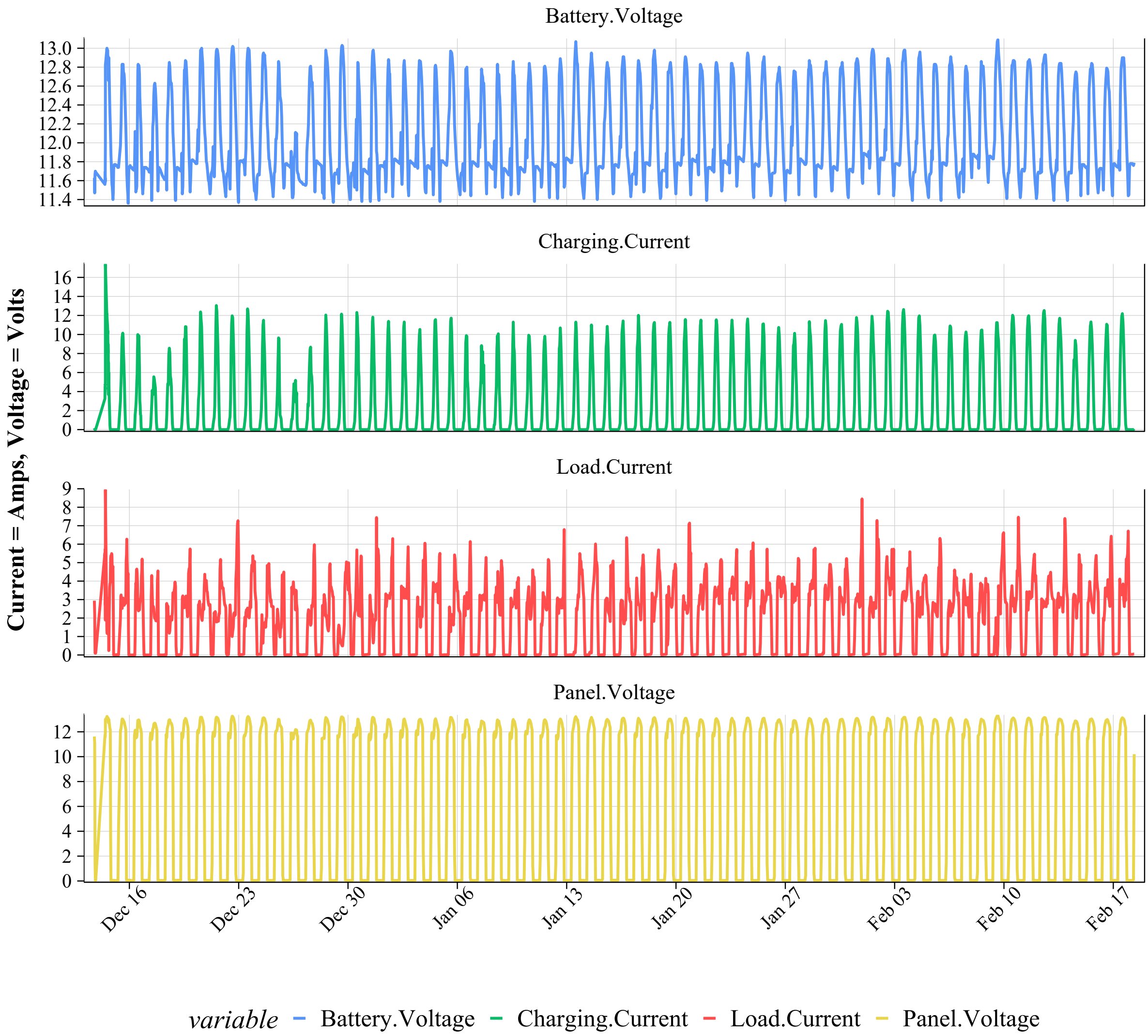

Figure 3.15: Kudang System Time Series Data

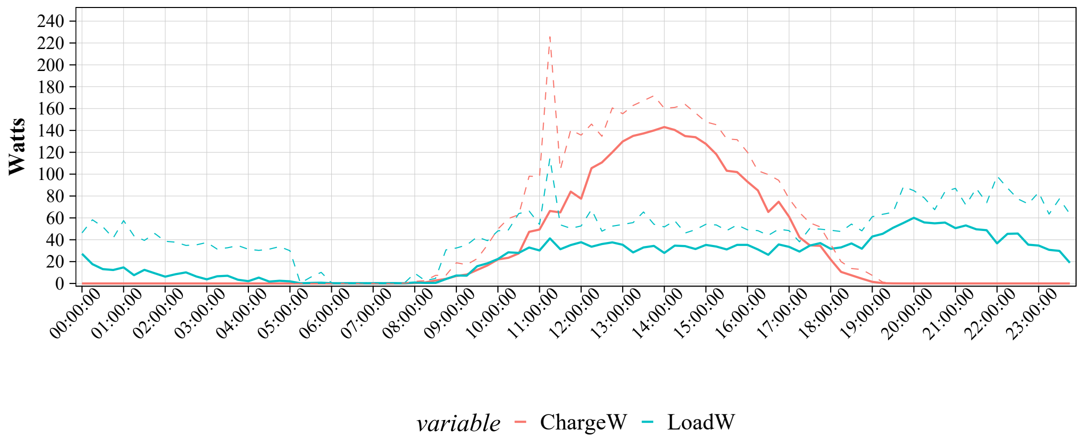

Figure 3.16: Charging and Load Power Profile, Average and Maximum

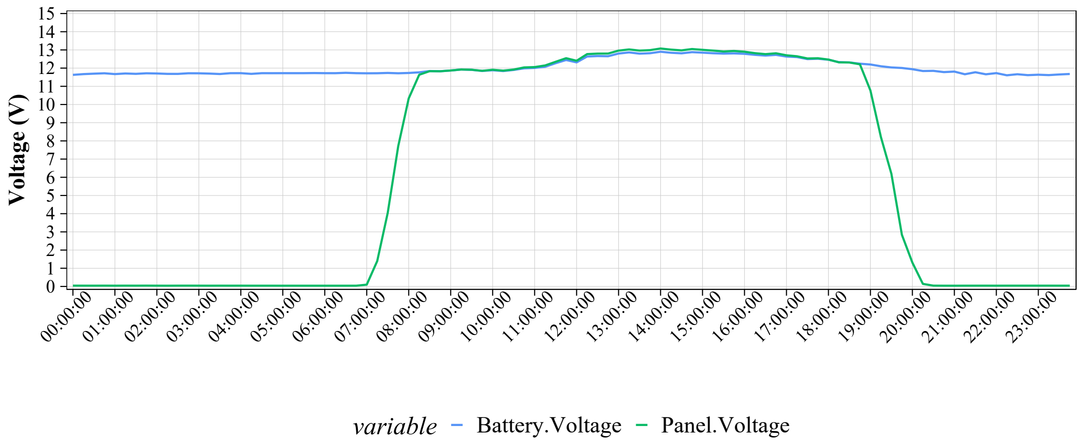

Figure 3.17: Average Daily Battery and Panel Voltage

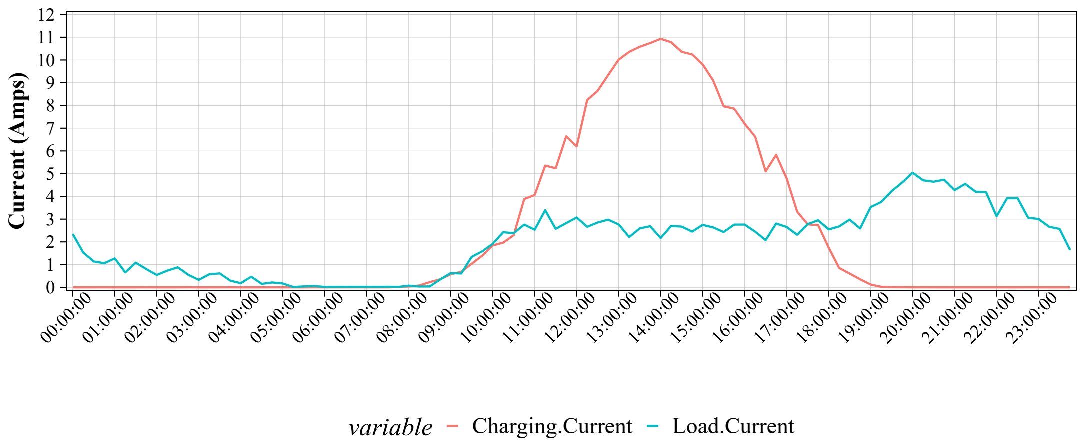

Figure 3.18: Average Daily Charging and Load Current

Financial State of the Projects

An audit of the project **financial data** captured the income and expenses attributed to each project. Project log-books had some gaps and did not track accumulated savings (see Figure 3.19). Financial data was gathered at three of the seven schools covering the ten month period October 2012 through July 2013. The primary income generated from the projects was through mobile phone charging. A single phone charge was priced at 5 Gambian Delasi (GMD), roughly USD $0.11 in 2014, and administered by the school staff. Monthly revenue was averaged between 500 to 1500 GMD (USD $11.5 to $35.5).

School staff were given free access to the mobile phone charging scheme. By interviewing staff on their usage of this service, it was estimated that an additional 30% more potential revenue could have been collected if they had paid the standard fee.

Expenses for the projects were comprised primarily of line items that did not go to directly supporting the technical components or operational costs. Expenses included transport fees, school improvements, foodstuffs, wedding expenses, and head teacher communication expenses. Notably, there were no system or maintenance related expenses within the logs.

Additional Sustainability Issues

At the Sambel Kunda project, the school headmaster explained the income of the project was dependent on the support of the local community as customers for the mobile phone charging scheme. In fact, it was not the only one available in proximity of the community and it was understood that, if desired, the community members would patronise these competitors. It was therefore important that a good relationship was maintained between the project and community to avoid loss of support. Given the type of benefits that the project provides: lighting, an additional source of income for the school, and a fringe benefit for teachers, the implication is that failure to provide these benefits would result in less community patronage of the mobile scheme.

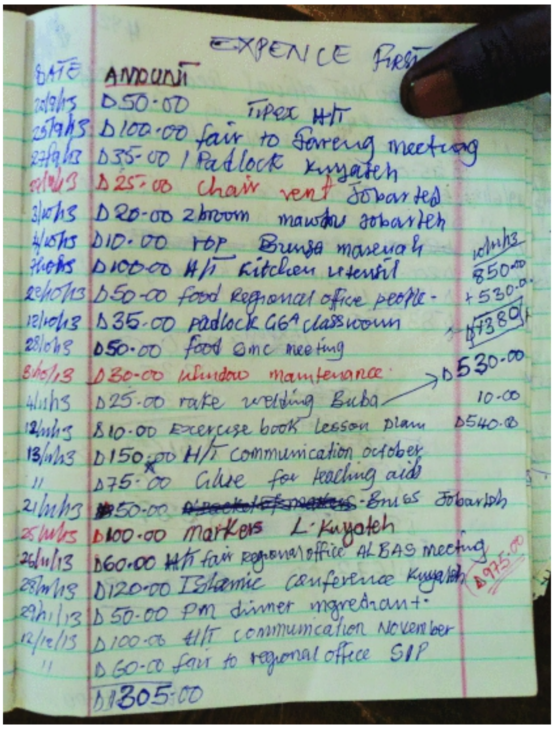

Figure 3.19: Gambia Project Financial Logbooks at Sambel Kunda

The **repair cycle** for the projects occurred yearly and were provided by the University. This was demonstrated at the Sotokoi Lower Basic Primary project which was found to be non-functional. The University staff troubleshooted the problem and ultimately repaired the system to working order. During the year between visits by the University, the school headmaster had asked a local person, lacking any formal training, to repair the system as they thought it was not performing properly. The fix included bypassing the charge controller which left the battery storage without proper protection and exposed them to potential damage by excessive charging and discharging.

It was observed that day to day **operational management** of the system was strongly influenced by the school leadership at each primary school. The Community and SMC members did not readily self-identify themselves as owners despite the project being badged as “community-based”. While it can be assumed that school headmasters were acting in the interest of the community, the role educational appeared to dominate any decision-making in the project – shown by the investment in materials for the school.

Figure 3.20: Sotokoi Lower Basic Primary under repair

Discussion of the Sustainability challenges

Several sustainability issues were observed during the visit. These included a lack of availability of local technical skills, insufficient revenue generation, and a hybrid and ambiguous ownership structure that reduced local agency over the project.

Technical capacity of the operators was found to be lacking at all locations. System inspection had to be completed by University staff with little meaningful input by the local operators. There were no instances where successful repair or maintenance activities had occurred. The panels at most systems were caked with a thick layer of dust when inspected though the SMC reported that they were regularly cleaned. The attempted repair at Sotokoi highlighted the need to for increased technical training for the local owners to fully manage the technical aspects without external assistance. Here, the lack of skills may have damaged the batteries due to the untrained repairman's removal of electrical protection devices on the system – despite their good intentions.

Insufficient revenues from the income generating activities was potentially a major long-term challenge. System capital costs (excluding labour costs to install as this was done by University staff and students) was roughly USD $7,000. Even the best performing school's yearly annual revenue of USD $450 would be insufficient to cover long term asset replacement costs. The other two schools had even worse financial performance. With the current arrangement, where the University is responsible for raising funds for replacement and carrying out the repairs, this issue is mitigated. In effect, this arrangement subsidises energy use for public benefits by prioritising this rather than the income generating activities that would be needed to support equipment expenses. As a result, if the dependent relationship between project and University were to break down or become unfeasible in the future, the projects would likely be unprepared to solely take on the financial burden of equipment replacement.

The hybrid ownership arrangement created uncertainty on the roles and responsibilities of the community, operators, and University. A critical gap in maintenance and repair process was most apparent during the repair works at Sotokoi. The systems have benefited from a strong initial system design, owing to the University staff's expertise and sourcing of high-quality components. However, in the case of Sotokoi the fault appeared only months after the previous visit. This left the system under-performing for many months until the next visit was planned and undertaken. Due to uncertainty in the ownership arrangements, operators at other projects were hesitant to undertake repairs or even touch the system without University approval. The physical distance and cost to repair a system on a yearly maintenance cycle is extremely high. This experience has shown that a more clearly defined ownership is needed to make decisions on the project. With the current role of the University as the technical and financial backstop to the project, their own ability to continue to raise funds, source equipment, and provide the necessary technical expertise into the future must also be considered in a sustainability assessment.

Conclusions and Recommendations

The Gambia Project has provided a modest but impactful level of electrification at the rural schools in the Gambia through the use of renewable energy, the efforts of staff and students at the University of Strathclyde, and the local community. However, the long-term prospects of the projects remain strongly dependent on the University's continued financial and technical support. It is likely that the handful of issues experienced will reoccur and, should the University step back from its supportive roll, will lead eventually to sustainability problems. Although it has not been the intention of the programme design (further discussion on this point follows), true self-sufficiency of the projects, in either individually or as a collective of supportive projects, is currently a distant prospect. It is worth noting that the University has to date continued its commitments to the Gambia project and has completed a new off-grid project in 2019.

The programme has provided mechanism for continued learning on how to appropriately support each project in the future. The University involvement has steered the projects towards a less prescriptive model that is instead ready to learn about emergent sustainability issues. Although there has been no official impact evaluation on the programme, it has surely positively impacted communities though the provision of electricity access as well as benefited students and staff from the University with opportunities to learn and establish international relationships.

Despite the current programme arrangement, the intention has been to move projects towards more self-sufficiency. Therefore, this remainder of this section seeks to clearly offer short and long-term recommendations for the programme to address these issues. The issues include: lack of local technical expertise, financial inviability, and an (over) dependence on external support.

There are several options to address the **lack of local technical expertise** in the short-term. First, develop training programme for several local staff members to monitor the system, identify key faults, and build decision-making on when to intervene and when to arrange for more technical support. Training several people per location will help support knowledge retention and provide more resources for this task. Second, establish a supply chain of local technicians that can be called upon to assess and repair the system if need be during the periods when University staff are not in The Gambia.

Since the systems are fully utilised, improving the **financial performance** of the projects involves shifting the proportion of energy use towards commercial activities, that is mobile phone charging for a fee. While the free charging is appealing to educators, switching a portion of or all of their charging to a fee-based system will provide a substantial boost to income. Active marketing should be explored which promotes the need for increased community support the project by ensuring their mobile phone spending goes to the projects as much as possible. Finally, limits should be set on the acceptable items and amounts that can be expended to the project that are not directly related to the system maintenance and operations.

The **over-dependence of the projects** on the University likely has no short-term fixes and should be approached incrementally. If agreeable and seen as critical by all stakeholders to improve overall project sustainability, a road-map could be developed to change the nature of the ownership arrangement. A higher level of self-sufficiency will ultimately require the hand-over of responsibility for maintenance and repair of the systems and perhaps most significantly the financial burden. A transition of this nature can be a valuable research experience and have significance for other organisations desiring to transition projects towards higher self-sufficiency. Key steps for the transition will include:

- Re-establishing the University role in the projects especially during after-care. As a general strategy, the University should avoid stepping into any functions which can be handled locally.
- Formal full handover of projects to a responsible local organisation(
  s) mandated with maintaining the ongoing sustainability of the project, or, decommissioning if appropriate.
- Sourcing a local supply to replace existing equipment.
- Socialising the results of financial cash flow modelling with communities and development of cost-reflective tariffs.
- Building a technical resource to handle installation, training, and maintenance of projects on a more reasonable cycle.
- Exploring national, regional, and local support networks for off-grid rural electrification. By providing a public good, lighting at schools, this is well aligned to receive funding from formal public sources. While full cost coverage may not be

possible some level of public financial support should be sought.

3.3 Chapter Conclusions

Chapter 3 has reviewed the evidence for off-grid project sustainability and found mixed sustainability performance overall. Over 80 distinct sustainability issues were identified, and there was an inconsistent approach to defining and measuring sustainability amongst the projects. An extensive analysis of projects drawn from the literature included a survey of off-grid project sustainability experiences worldwide and an in-depth study from three individual projects involving Non-Governmental Organisations (NGOs). The remaining challenges justify additional work to refine techniques to address project sustainability – this assertion is a foundation for the efforts in later Chapters in this thesis to develop these techniques. The Chapter also highlights the importance of the operational phase of a project towards sustainability. It is shown that there is a complexity between the connections of available information, decision-making, and operator actions to ensure ongoing sustainability.

Section 3.1 reviewed a diverse range of off-grid rural electrification projects deployed throughout the world. This literature considers project sustainability a critical aspect to the success; the literature review captured over 80 distinct items in total, the most frequent identified in each sustainability category is shown in Table 3.1. The table reports on the proportion of item occurrence within the category, % within all articles reviewed, and % of total count of all issues. However, most articles were concentrated on issues within specific categories, leaving gaps in the evaluation where there was no coverage.

Table 3.1: Top Sustainability Issues found by Category

Category and Item	Count	% in category	% of articles	% of total
Technical				
under-sized system design	4	14.8	13.8	2.6
inability to manage growth / changes	3	11.1	10.3	1.9
low quality components (batteries)	3	11.1	10.3	1.9
unexpectedly high component failure	3	11.1	10.3	1.9
Organisational				
after sales care / support	7	15.9	24.1	4.5
limited operator skill levels	5	11.4	17.2	3.2
limited local technical skills	4	9.1	13.8	2.6
operator ability to manage change / growth	4	9.1	13.8	2.6
low local entrepreneur involvement	3	6.8	10.3	1.9
Economic				
unfeasible financial model	7	28.0	24.1	4.5
limited customer ability to pay	4	16.0	13.8	2.6
Environmental				
inconsistent battery disposal	1	100	3.4	0.6
Social				
user skill levels	4	11.8	13.8	2.6
community participation / engagement	3	8.8	10.3	1.9
local ownership model	3	8.8	10.3	1.9
low user satisfaction	3	8.8	10.3	1.9
External				
enabling political environment	4	16.0	13.8	2.6
available spare parts	3	12.0	10.3	1.9
poor logistics	3	12.0	10.3	1.9
sufficiently developed supply chain	3	12.0	10.3	1.9

Many projects related only a subset of the issues, implying that any given issue are either not relevant or has been overlooked by the authors. The extent of the issue, relative importance, factors which produce the issue, interrelation of one issue to the next and the impact of the issue is often only addressed at a superficial level. This is unfortunate as it leaves future designers, taking the lessons from these reports for their own projects, with many subjective choices to make on how to handle these issues.

The reviewed literature establishes that a host of issues are still preventing projects from being sustainable and many projects are seen as susceptible to failure. This includes recent projects which appear to be devised thoughtfully but still experience challenges that put into question their long-term sustainability – Section 3.1 covered over 20 projects from the early 2000s to present. This trend appears to apply to both older and more recent projects. Additionally, three case studies that involved sustainability evaluations by the author of this thesis were documented to build up a more comprehensive narrative of project sustainability issues. A summary of key insights that were captured from the case studies are:

- Muhuru Bay Micro-grid
  - An incident of theft and subsequent disappearance of the local operator occurred at the project.
  - Operational aspects of rural off-grid projects that are also businesses were became difficult to maintain. Following the theft, there was vacuum of skills which included basic charging management, customer management, sales and marketing, financial accounting, and managing competition.
  - The inter-relatedness and complexity of the relationships between different sustainability factors was demonstrated. A lack of skills led to lowered utilisation of the resources and lowered financial performance. Shady business practices by the outgoing operator undermined the customer's trust in the business resulting in non-payment. Additionally, the sequence of events was important, initial problems snowballed into the next.
  - Adaptability of the project owner was concluded to be the most important single aspect of the project's future sustainability.
  - The dynamic relationship of sustainability issues over time shown in the project suggest that the 'spot check' method, where conclusions are based on measurements at a single point in time, for sustainability evaluations may be insufficient to capture the root causes.
  - The sustainability planning during the project design stage overlooked a number of the potential issues that manifested in the project: owner train-

ing needs, ownership arrangement, handling competition, and responding to theft. Project modelling for Muhuru Bay was heavily dependent on techno-economic designs. This weakness was recognised by the implementing organisation, though robust modelling tools do not exist.

- Gambia Project
  - Technical capacity was severely lacking at all projects.
  - There was evidence of tampering from an unsuccessful repair attempt.
  - Revenue generation was insufficient at all locations.
  - Virtually no income was set aside for the system costs.
  - Expenses were mostly attributed to school-related expenses.
  - Dependence on the University to maintain and fund repairs resulted in a potentially long repair cycle.
  - A complex relationship was found in which, for one project, the community gave it preference for patronage on its mobile phone charging scheme, but this was dependent on it offering a free services to the school and staff.
- MREAP
  - A 2012 study found a wide range of challenges facing projects in Malawi: battery failures, insufficient project income, failed equipment, poorly sized equipment, limited local agency support, low management and technical support skills, lack of local community ownership, insufficient training, and potential for theft.
  - In 2016 a country wide comprehensive sustainability survey involving metrics from 4 sustainability factors and targeting solar PV projects at public facilities found that no projects were found to be 'fully sustainable'.
  - The infeasibility of the project economic model was the most significant single weakness - almost all projects had far too little income to support the long-term capital replacements costs. Projects faced particularly low scores in the following metrics: Community contributions, stakeholder meeting frequency (about projects), initial technical training, all types of ongoing

training, and existence of a formal project bank account. For the technical sustainability, the majority of projects undersized the batteries and panel and on average projects could only provide for roughly 60% of electrical energy needs.

- Refinements from the MREAP model contributed to generally improved sustainability prospects. This involved increasing community agency in design and procurement of projects, closely aligning project objectives to expressed community needs, added training for local organisations running the project, and requiring certification with the MERA, the national regulatory agency.
- Lack of sustainability was connected to the limitations of the community energy model which places ownership in the hands of the community, but comes with a need for a higher organisation capacity. Building and maintaining this capacity is a ongoing challenge for community energy projects.

This Chapter has presented a wide array of projects experiences and emphasised the challenges in implementing sustainable projects. Despite the gains in electrification that have been made, off-grid project sustainability is not a foregone conclusion. The tremendous future investments and hopeful rhetoric for off-grid electrification projects can be juxtaposed against the reality of sustainability that confronts the appropriateness this investment. It is argued here that the premise that projects are sustainable, which is needed to achieve universal access to electricity and enable other socio-economic benefits due to this access, is often invalid.

Chapter 4

A Model for Measuring Off-grid Project Sustainability

4.1 Motivation of Model Design

In Chapter 2, it was argued that limitations for modelling the sustainability of a project included an overemphasis on technical and economic aspects and an over-reliance on the design stage. Existing software packages do not use indicators for dynamic decision-making which reduce the realism of actors, such as the customers and operator who's behaviours can have significant impact a project's sustainability. Therefore, a novel model has been developed as part of this thesis to address these weaknesses with the objective of simulating a necessarily more realistic life-cycle of a project. The model will be shown to provide valuable insights in all project stages. Operational decisions, evaluations, and learning are all tied to a set of project-centric indicators and used by the customers and operator, throughout the project life-cycle.

The model simulates the 20-year life-cycle operations of a small scale off-grid electrical project in a developing country. Although the contexts are different within each country or sub-region, this model would fit in well with any of the three presented case studies. The simulation combines real-world data and fills in the informational gaps with sources from the literature and case studies. The simulation can be considered holistic as it produces an output of technical, economic, social, and organisational metrics based on available solar resources, load demand, and the results of operator actions and decisions.

An important innovation in the simulation involves creating a decision space for agents in the model. To simulate operational decision-making realistically in this context, dynamic decisions must be possible; data from the model must be accessed by the agents in order to adjust to the operational realities. A simplified set of indicators are used as the key metrics for these decisions. These include: achieved availability of service (proportion of kWh supplied to planned supply) for a private customer and a public customer, utilisation (proportion of energy supplied to maximum potential energy supplied), and level of financial savings.

The simulation progresses iteratively with each decision made by the operator and customers influencing subsequent time-steps. In this way, it is shown that the indicators are critical in the implementation stage of the project and indeed provide vital information for improving sustainability prospects. The importance of indicator based decisions are highlighted over several stages of the project life-cycle: during design of projects, operations, evaluation, and learning.

Model Value to Specific Project Stages

Questions considered in the **implementation stage** are: *How do operational decisions (limiting power supply, changing price, investing in training) impact sustainability of the project? What data is needed to make sound decisions? Is the project aware of the affects of the decisions that are made (or lack of a decision)?* During the simulation, time-series data of the indicators are produced, for further analysis of their evolution, interrelationships, and the impact of various tested interventions.

Within the **design stage** of a project, the results of the simulation offer an alternative to the current techno-economic optimisation software packages (i.e. HOMER) by introducing a data-driven decision mechanism, through indicators, and a basic framework for model actors to interact. The potential relationships between sustainability factors and subsequent scenarios that could occur are numerous and these have been under-defined in the literature. Therefore, the specific scenarios highlighted in this model have value both practically, but also as an inspiration for modelling other relationships which have not been included

The **evaluation stage** of a project provides the primary means to update the sustainability model, refine relationships between sustainability factors as they become clearer, and document the features of a project which prove particularly effective. Continuously improving the modelling of off-grid projects in developing countries provides a critical support tool that improves understanding, assists in forecasting, and testing interventions prior to implementation. An evaluation with a set of indicators consistent with earlier modelling efforts (during the design stage), produces a comparable real-world data-set. It is then important to study and account for deviations of the results between simulation and real-world. Encouraging and accelerating this feedback loop is critical to improve model-based project planning.

4.1.1 Comparison to Techno-economic Simulation

The model in this thesis offers several innovations over existing techno-economic modelling approaches (as described in Section 2.4). First, the model is more holistic in the sense that it explicitly considers technical, economic, social and organisational aspects. Techno-economic software optimisations typically involve only technical dynamics: solar irradiance, temperatures, load profile, and generation system characteristics. These simulations produce the electrical system output which then drives the economic analysis, providing a net-present value calculation of future costs. Yet this approach drastically under-represents the social, organisational, and indeed many economic aspects of a project that are equally important. Lacking the practicalities of a real-world project, that do involve the holistic set of issues, limits the relevance of simulations from techno-economic optimisations. In contrast, the thesis model adds a layer of information, in the form of indicators, that are used by the operator and customers throughout the simulation. Techno-economic optimisations have implicit assumptions over how project decisions are made, again limiting how representative the results are of a real-world project implementation.

In conventional simulations, the operator and customer decisions are simplified or ignored altogether. For example, there may be no possibility for an operator to set prices or to reduce or increase energy being supplied to one customer or another as neither the operator nor customer has an ability to change strategies throughout the simulation. While this level of granularity in the model may not be necessary for hourly- or daily- decision-making, it is insufficient to model medium or longer-term decision-making which may arise. This is important since this longer-term strategic decision-making is needed to respond and adapt to the conditions on the ground; or a else a project, "perfectly" designed would have no need to consider conditions which occur during operations. These decisions likewise can have an effect on sustainability. To address these issues a simple decision framework is included in the thesis model which covers: customer price elasticity of demand and a community retaliation/reward mechanism. These are chosen due to available and documented case studies that can inform this modelling effort, though it should be noted that little research exists currently that robustly defines these relationships. Therefore, the objective is to replicate the stylised facts around these mechanisms in the simulation such that a modelling framework can be refined when further research becomes available.

Before discussing these factors in detail, it may be important to highlight the weaknesses in conventional modelling as well as the implications it has on sustainability. First, from the available data sources suggest that it is reasonable to assume that customers will have a downward sloping demand curve (Walrasian demand function) [178]. This implies a demand decrease when prices increase. There is no explicit function within conventional simulations, instead, customers are assumed to be absolute price takers. Even if revenue is omitted and determining levelised cost of energy is the ultimate objective, as is the case in a techno-economic optimisation simulation, there is no explanation from the model as to the effect on the input demand when a profit margin is added (and to what extent). If one assumes there is any effect, then it would most likely impact the size of key components (renewable generation sources, battery storage, etc.) as a customer demand, at particular price, is varied. Assuming that for a given customer (or aggregation of customers) an entire demand function exists, and that dynamic pricing is an option, even if only through manual adjustments by the operator, then a simulation result which only considers a single price can only be valid for that case.

A second issue is with the relationship of the community and project. Chapter 3 highlighted various social challenge such as possibility of theft, lack of local support, and loss of credibility. It is entirely possible that a given project faces one or all of these issues (or indeed issues not yet identified in the literature). As a whole, these issues can be perhaps better described as "community acceptance". Clearly, lack of community acceptance can manifest differently. As seen at Muhuru Bay (see Section 3.2.2), the publicly known theft reduced credibility and made collection of funds more difficult if not impossible for some customers. Theft may arise for many reasons including relative poverty, jealousy, lack of basic security, exclusion from the services and has a direct and immediate impact on the project as equipment or funds are lost. For the Strathclyde Gambia project (see Section 3.2.3), the issue of private demand being linked to free electric services provided to the school is yet another potential issue that both helped and hindered its sustainability. Villagers nearby the school preferred using its mobile charging kiosk as it also supported the lighting provision at the school. When the public lighting was perceived as insufficient due to unavailability, customers instead choose competitors for business - penalising the scheme. All of these mechanisms have serious implications for the sustainability of the project and are clearly related to other elements of the project including technical and economic performance. Modelling of any social mechanism is wholly absent from conventional techno-economic models. Conventional design exercises instead combine a techno-economic output with separate, out-of-loop, consideration of these issues. While modelling social interactions is undoubtedly challenging, the decision to reduce the simulation to a simplified techno-economic model again raises questions towards its validity. If done so, the overall result will only be valid while the social system, consisting of assumptions or other disconnected modelling, remains valid.

4.2 Model Design Methodology

This section modelling approach each sub-component of the thesis model as well as a description of the data-set used. To ensure the simulation is representative of a real-world project, real-world technical and project data is used consisting of temperature, irradiance, and load data. A 'reference' model[1] is built to validate the thesis model results where applicable. The optimised system design provides a useful comparison case to show the strengths of the thesis model. Both thesis and reference model utilise the same set of input assumptions.

This section is organised as follows. First, the data-set and data handling is described. Second, the general assumptions used in the modelling are defined. Third, the reference model simulation results are discussed. Fourth, the thesis model is then defined according to its major components: initialisation, operation, and operator decision framework.

4.2.1 Description of data for systems and weather station

Raw data originates from 10 off-grid PV systems in a close proximity (< 100km) in Southern Malawi. These systems were fitted with remote sensing units and data loggers that captured time-series data including: panel voltage, charging current, battery voltage, load current, local ambient temperature, and irradiance [179]. This data was used to create representative base load profiles and to capture solar irradiance and temperature profiles.

The same data is used within the reference model to create an 'optimal' system design and simulation. Although the actual system PV and battery components are known for the corresponding data-set, the design approach in the thesis model corrects the design errors due to erroneous demand estimation in the real-life projects [109]. The error was primarily due to the challenges of using survey data and limited available consumption data to estimate. Additionally, the original design used an ad-hoc method that significantly oversized the equipment. The ad-hoc design was dropped in

[1]The reference model is built using the HOMER Legacy software package

favour of a computer assisted design that minimises costs with a limitation of 0% maximum annual capacity shortage. Furthermore, it is assumed that the demand estimate is error-free and as such use the measured profiles as input in the design stage. This approach allows for comparison between the simulation and reference model results while retaining the realism of the data. The thesis model is simplified for this comparison, removing some of the complexities (described in detail in Sections 4.2.6 and 4.2.7) which are irrelevant in the reference model and would have a significant impact on the technical and economic results.

The daily consumption profile for all 10 sites is shown in Figure 4.1.

Although all 10 locations are graphed, for the purpose of the simulations the two loads used to initialise the model are: *Gumbwa Health Post* and *Gumbwa Staff Room*. Incidentally, these loads are both located within 100m of the weather station. The intention of choosing these two loads was to include one real-world load which was primarily used for commercial purposes (Gumbwa Staff Room) and one which was primarily supported a public structure (Gumbwa Health Post). All 4 Gumbwa systems exist within 100 metres of each other but are all separate standalone systems. The second motivation for using Gumbwa systems is that they are at the exact location of the weather station – hence this would minimize any errors even a short distance might introduce. For the simulation, both loads are scaled by 200% simply for the aesthetics of improved visualisation of values.

Daily average temperature and daily total irradiance, by month, is shown in Figures 4.2 and 4.3. Daily irradiance varies between 5835 and 8212 W/M^2 and daily average temperature between 24 and 32 C°.

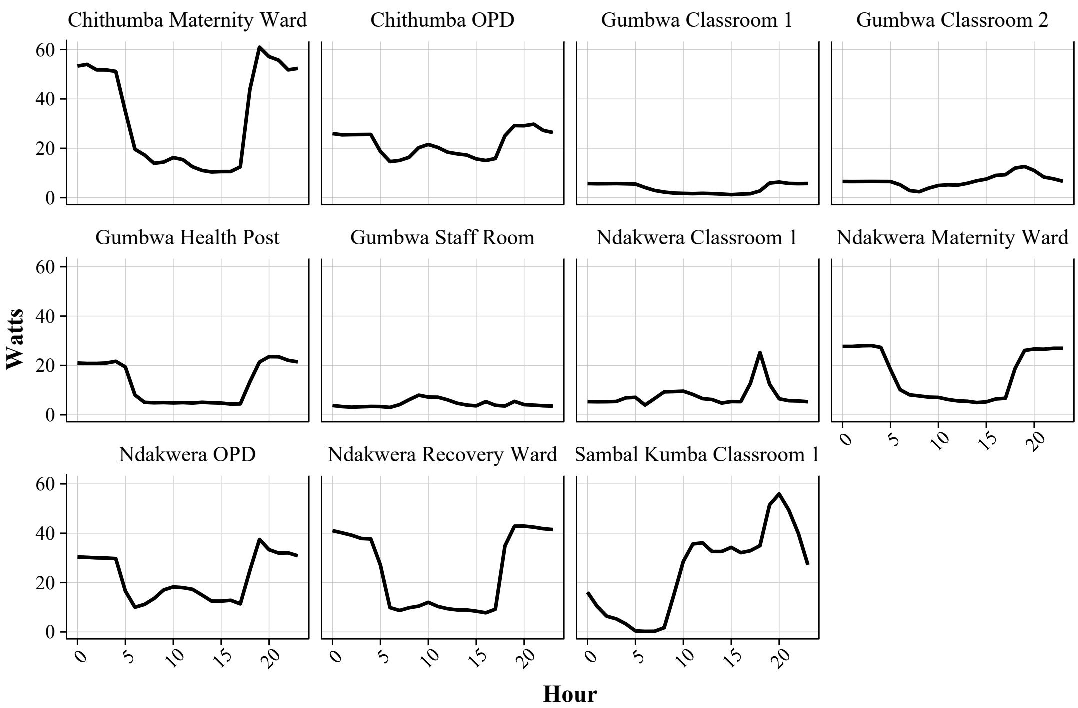

Figure 4.1: Daily Consumption Profile

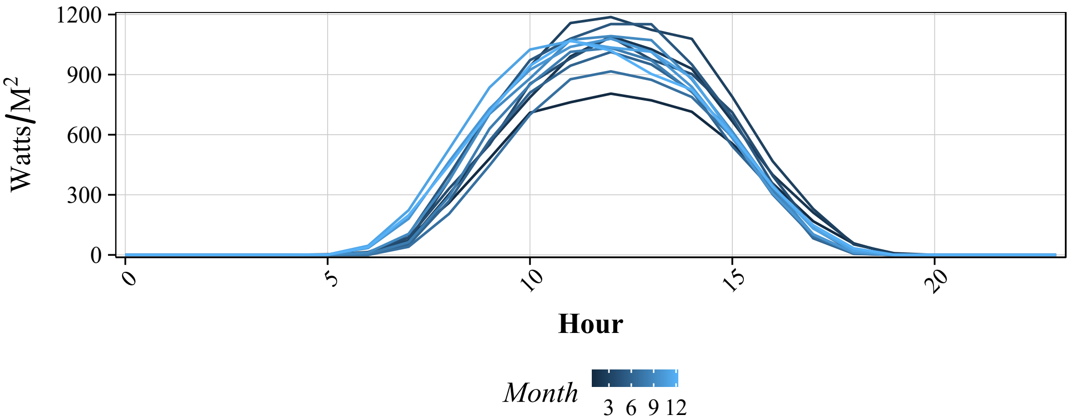

Figure 4.2: Daily Irradiance Profile

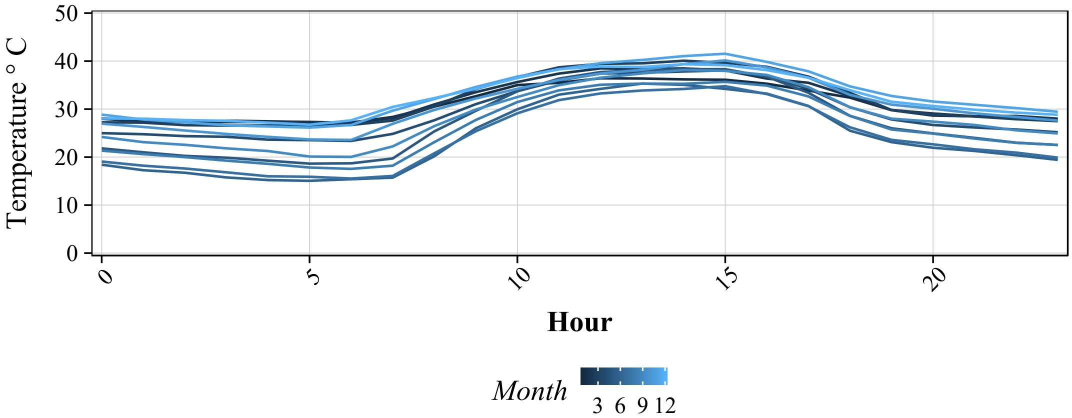

Figure 4.3: Daily Temperature Profile

4.2.2 Data Handling

Real-world data invariably requires pre-processing prior to use. In the case of the present data-sets, this involved first standardising irregular increments to 60-minutes. Second, there was a limited number of missing data over the sequences. A combination of interpolation and imputation was used, depending on the size of gap. For gaps of 6 hours or less, a linear interpolation is used between the two known points. For gaps greater than 6 and less than 72 hours, the monthly average hourly values are substituted. Gaps larger than 72 hours are left as missing data (only 5 data points). This treatment is applied to all data (systems and weather) used during initialisation of the model.

4.2.3 General System Data used in Simulation

The system is selected to be generally representative of a small off-grid project present in the country case studies: Malawi, Gambia, and Kenya. A distribution network and related network effects are not modelled, though the results are still relevant for low-maintenance small scale systems, including micro-/mini-grids. Micro-/mini-grids can be assumed to have an increased financial burden, higher potential for technical losses, and higher organisational capacity requirements (for example financial, technical, and managerial). In contrast, by modelling a relatively simple stand-alone PV system, greater attention can be placed on analysing sustainability challenges rather than the technical details.

As shown in the figure, the system can be described as a stand-alone PV system with battery storage, two loads, a charge controller, and inverter, as shown in Figure 4.4.

Data sheets are used from commonly available equipment within Malawi. Initial capital costs are estimated from a study of 10 past projects (rated from 300W to 1000W) in Malawi and scaled to PV and battery capacity size [180]. Converter costs (including both a charge controller and inverter) were 19.11% of the combined PV and battery costs. Installation was 35.74% of combined PV and battery costs. All other

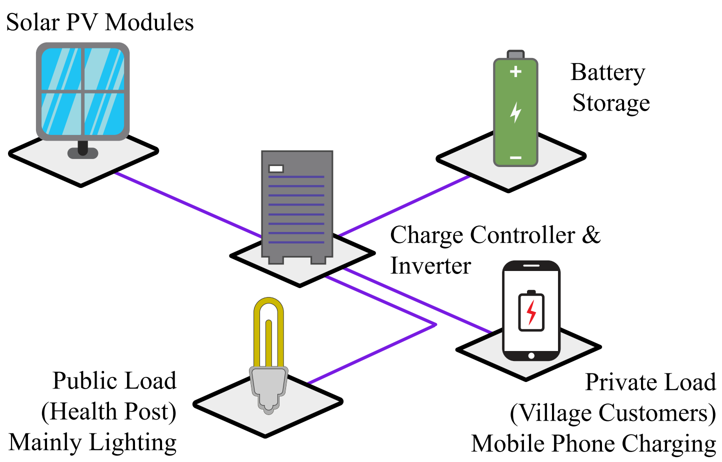

Figure 4.4: Main System Components

costs, including sundries, light bulbs and other items were 75.05% of combined PV and battery costs.

PV and battery cost estimates are based on linear regression model that was conducted in a 2016 study field study that checked local prices from local suppliers [109]. The regression co-efficient for PV panels, from 27 quotes, was \$1.555/Wp. The regression co-efficient for local prices of batteries, from 15 vendors, was \$0.168/Wh. Therefore, once an optimal system size is found, the expected costs can be scaled according to the PV and battery size.

For reference, all parameters used throughout the modelling are shown in Table 4.1

Table 4.1: General Simulation Parameters

Parameter	Notation	Value
Technical		
Temperature Correction Factor	P_{mp}	-0.45 per 1°C
Temperature at Standard Test Conditions	T_{STC}	25°C
PV Efficiency (Std test conditions)	-	15.87%
Depth of discharge limit	DOD	50%
Avg. PV Lifetime	-	20 years
Avg. Converter Lifetime	-	10 years
Avg. Battery Pack Lifetime	-	3 years
Combined Inverter & Charge Controller efficiency	-	95%
Ross Coefficient	k	0.0563
SOC Upper Charging Threshold at time t-1*	$SOC_{H,t-1}$	.98
Maximum annual capacity shortage**		0%
Load 1 Scaling (Public/Free)		2.0
Load 2 Scaling (Private/Paying)		6.0
Initial yearly consumption, L1 to Total Load $(L_1 + L_2)$		47.1%
Yearly load growth		5%
Panel Losses		
Wire Losses	S_1	10%
Module Mismatch	S_2	10%
Module Aging	S_3	8%
Dust or Dirt	S_4	11%
Battery Losses		
Battery Charging efficiency	$\eta_{b,in}$	92%
Battery Discharging efficiency	$\eta_{b,out}$	92%
Round-trip efficiency		84.6%
Economics***		
PV CAPEX	-	$1057.40
Battery CAPEX	-	$806.40
Convert CAPEX	-	$283.67
All Other CAPEX	-	$2275.80
Total CAPEX	-	$4423.27
Yearly O&M Costs	-	$442.33
Annual real interest rate**	-	6%

*The reference model does not use this parameter; only relevant in thesis model

**Thesis model does not use this parameter; only relevant in the reference model

*** USD in 2016

4.2.4 Techno-economic Optimisation Comparison Model

The general parameters in Table 4.1 are used to produce a reference model to order to size the system. The specific software package used for this sizing is HOMER Legacy [112]. Given the input data, the optimal system design has a 680W PV array and 4.8 kWh of energy storage. Sizing of this system is based on the software's minimum cost optimisation result. Further critical results of the optimal design that has been calculated are shown in Table 4.2. To increase the value of comparison, the reference model and thesis model use many similar assumptions and share relevant parameters.

Table 4.2: Techno-economic Optimisation (Reference) Design Results

Parameter	**Notation**	**Value**
PV Capacity Rating	P_W	680 W
Battery Capacity	R_B	4.8 kWh
Converter Size		250 W
Total Net Present Value	NPV	\$12,142
Cost of Energy per kWh	-	\$1.685
kWh/yr Production	-	1,158 kWh
kWh/yr Consumption, L_1	-	296 kWh
kWh/yr Consumption, L_2	-	332 kWh
Excess Energy/yr	-	461 kWh

4.2.5 Thesis Model Components

A model is developed in this section which allows for the exploration of complexities present in modern off-grid electricity projects as well as the consideration of the role of indicators in the decision-making and ultimately, sustainability performance of a project. The model definition is organised into three main components: initialisation, operation, and operator decision-making. The remainder of this section defines these sub-components.

4.2.6 Initialisation Modules

Initialisation modules include the simulated weather and load data, component breakdown schedule, initial operator characteristics, initial market and community characteristics, electrical system characteristics, and other model assumptions.

Generated Weather and Load Data

As shown in Figure 4.5, real-world data from Malawi MREAP projects are used for temperature, irradiance and loads. Multi-year synthesized data is generated from the statistical characterisations of the 1-year Malawi data. For a model with hourly increments and concerned with long-term sustainability issues, it is sufficient to match daily profile and seasonal averages of the respective variables.

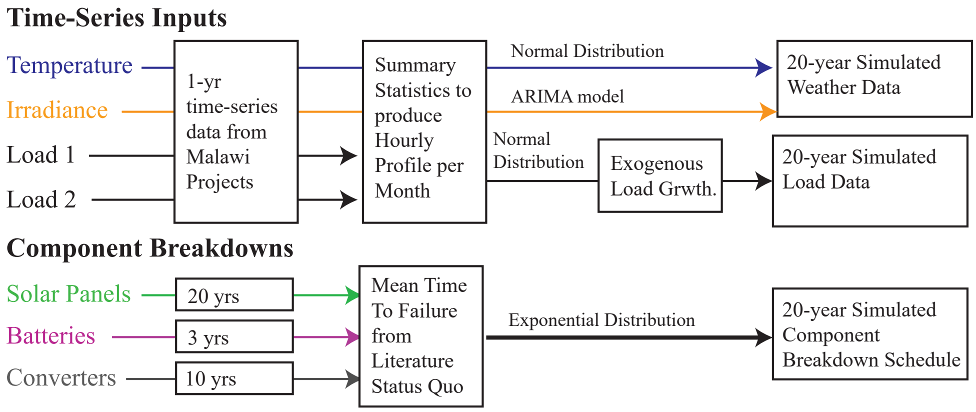

Figure 4.5: Initialisation of Weather and Component Breakdown

The cleaned temperature and load data-sets are split into monthly sub-sets. Within each monthly sub-set, the average of hourly value and standard deviation is found. For solar irradiance, capturing the auto-correlation from one day to the next is critical to model the off-grid context [181], therefore an ARIMA model is developed. Projects are often designed with an expected 'days of autonomy' where it is assumed that several days of low sunlight may occur and, if there is insufficient storage, there may reduce system availability. The parameters for forecasting are summarised in Table 4.3.

The forecasting approach for weather and load for the simulation is as follows:

1. Averaged hourly values are calculated, for each month for each variable: Load

in Watts (W), Panel generation (W), Temperature in Celsius. This forms an average daily profile for each variable for each month.

2. Monthly load in Watt-hours in and panel generation, in Wh are separately summed. Monthly average temperature is used in Celsius.
3. Daily Average Temperature and Load is modelled as a Gaussian distribution, with parameters as in Table 4.3. Longer-term historical data-sets might be used to define different monthly distributions for weather and load, but in this case only the gathered data-set was used. As there was only 1 observation of mean monthly temperature or average load, a gaussian distribution was considered sufficient.
4. Daily Irradiance, (Daily sum W/m^2 at the tilted angle of 16°N) is modelled with an ARIMA model of the form ARIMA(1,0,2) using the R package *forecast* and *auto.arima* functions [182]. Relevant parameters for the resulting model is shown in Table 4.4. This package selects the best fitting ARIMA model of various forms and fitted to a given time series data-set.
5. Daily Load Consumption and Average Temperature data are generated from the respective monthly distributions defined in Table 4.3. Daily Irradiance data is generated with the *simulate.Arima* function [182].
6. With daily values of variables known, hourly profiles are generated first by determining the proportion of the forecasted daily values to the monthly average profile, for each respective variable. Hourly values are then scaled according to this proportion. For example, in the cases that load is double the typical daily load, the daily load hourly values would equally be doubled. This process occurs throughout all generated daily profiles.
7. Given the small initial load sizes, loads are scaled. Load 1, the private load, is scaled by 2, while Load 2, the public load, is scaled by 6. This has a trivial effect on the results of the simulation as both are incorporated already into the design assumptions. This is done to reduce the potential for very low load days, which makes visualisation more challenging, as well as to set the base consumption between the two load types as roughly equivalent.
8. Load growth is applied to each individual base load at a yearly compounding percent: 5%. This is applied monthly. This can be expressed by: $g_{L,1} = g_{L,2} = 1.05$

9. The resulting loads are considered unmodified base loads. The daily energy consumption of the unmodified loads are given by $L1_{base}$ and $L2_{base}$

The resulting load is referred to as the 'base simulated load profiles' and can be considered the intrinsic load demand assuming access to electricity service.

Table 4.3: Forecasting Parameters for Temperature & Load

	Temp. ($^{\circ}C$)		**Load 1** (L_1, Wh)		**Load 2** (L_2, Wh)	
Distribution	Gaussian, $f(x \mid \mu, \sigma^2)$					
Parameter	μ	σ^2	μ	σ^2	μ	σ^2
Month						
Jan	31.095	1.316	111.734	100.491	240.070	86.637
Feb	31.634	1.342	132.040	68.801	175.243	33.678
Mar	31.887	1.233	149.328	85.030	191.006	40.837
Apr	29.419	1.637	125.347	46.994	251.679	80.847
May	27.021	2.068	109.129	46.164	164.454	40.329
Jun	24.077	1.704	76.673	40.718	324.307	75.738
Jul	24.046	1.849	83.851	46.407	267.849	28.097
Aug	26.127	2.265	38.524	29.583	349.203	100.096
Sep	28.494	2.656	66.702	39.440	433.669	104.606
Oct	30.986	2.348	137.427	50.537	376.249	69.959
Nov	32.949	2.352	93.352	44.269	355.580	48.408
Dec	32.478	1.183	86.166	58.444	333.903	55.163

Table 4.4: Forecasting Parameters for Irradiance ARIMA Model

Parameter	**Value**	**Std. Err.**
ar_1	0.8870	0.0639
ma_1	-0.4513	0.0857
ma_2	-0.2363	0.0654
mean	7022.3420	248.7096
σ^2	2828372	
log likelihood	-3023.67	
AIC	6057.34	

Component Breakdowns

Failures of system components occur for a variety of reasons but can include random failures, lightning, vandalism, installation problems, manufacturing defects, operating conditions, and poor regulation. The method for handling component breakdowns is outlined in Figure 4.5.

On initialisation, a breakdown schedule is created for each sub-component (converter, PV panels, and batteries) with the time-step set at monthly increments and drawn from an exponential distribution. The exponential distribution is selected due to simplicity for mean time to failure modelling as it has a constant failure rate and is sufficient for the scope of the thesis model. The distribution density function is defined in Equation 4.1. The exponential distribution is suitable as it is commonly used for failure models. Ten (potential) failures are generated per component are generated, sufficient to cover the 20-year time-span of the simulation. Although the method is described here, the specific breakdown schedule, by component, used in the simulation is shown later (see Table 4.7).

The rate parameter, λ, indicates the number of months until average breakdown occurs and is given, for each component, as: $\lambda_{panels} = 20 * 12$, $\lambda_{batteries} = 3 * 12$, $\lambda_{converter} = 10 * 12$. These values are commonly used practical assumptions on typical lifespan of these components.

$$f(x) = \lambda e^{-\lambda x} \tag{4.1}$$

The approach of handling breakdowns, for example in the reference model, is to create a deterministic breakdown schedule. The exact breakdown date is known which eases the computation of depreciation and hence financial modelling. Unfortunately little to no research exists regarding the asset degradation of these systems which would facilitate modelling their detailed failure modes[2]. Nonetheless, the literature and practical experience suggests that there is significant variation in breakdowns with some occurring only weeks or months after original installation. This suggests that a deterministic schedule is unrealistic for off-grid electricity access projects in developing countries. A series of breakdowns, for example, occurring in succession in the first year of operation may overwhelm the financial facilities of the project. Therefore, without

[2]In one study, system failures levels are captured at a given period, but lack sufficient detail to facilitate how and when these failures occur [159].

further empirical data, the probabilistic modelling approach described is preferable to the deterministic approach as it provides a more representative breakdown schedule.

Note, that while the functionality exists in the model to generate any number of desired breakdown schedules, in practice only a single randomised scenario is used. A logical area of future research would employ a Monte Carlo technique to explore the impact of variation of these distributions, as well as load and weather distributions. There are a number of examples in the literature, applied to off-grid project design, where stochastic methods have been used [183–186]. While such an approach is considered research merit by the author, it was considered out of scope in this thesis it may have detracted attention from already important insights that were captured.

Initial Operator Conditions

Critical to the model is the interaction of a micro-utility and its operator as a decision maker throughout the simulation. This requires a base set of assumptions on the initial circumstances, operator, market and organisation. A fully descriptive understanding of how all decisions are made, in all possible circumstances of operations, is not intended. Individual contexts may present a seemingly unlimited number of potential scenarios that modelling each would prove intractable. It is argued, instead, that common and important issues which are recognised through the literature, but not necessarily modelled, offer the most immediate value for incorporation into this model. Moreover, in order to demonstrate the importance of employing indicators, a mechanism is needed for making decisions on a regular basis throughout the project lifetime. This section defines and justifies the initial operator conditions of the model.

The 'Operator' is the entrepreneur responsible for making decisions, ensuring technical operation of the system, establishing customers, managing customer service, and ensuring an agreeable relationship with the community. In practice, for small off-grid projects, operators are usually selected for their knowledge of the specific community and relatively high level of technical and business aptitude. Unsurprisingly, the performance of a project in achieving its objectives, impact or sustainability focused, is strongly linked to the operator's own performance. The ability of the operator to make a decision, informed by observations and data can make or break a project's sustainability prospects.

The basis for operator and skill modelling is supported from the literature, for example, the AFREA toolkit stated: "facility staff will usually be responsible for day-to-day system control and use and routine maintenance. Their capacity to meet these responsibilities must be built and, as staff change, rebuilt and refreshed with training..." [9, p.50]. The importance of adequate skills for project operation was supported further in the MREAP (Section 3.2.1), and Muhuru Bay case studies (Section 3.2.2). Although training and maintenance of skills was identified as an important factor for project sustainability, and critical to operation of the project, it is surprising the limited extent to which this aspect has been modelled.

In the thesis model, the operator is a principal agent making decisions within the local market for electricity. An initial **operator skill level** is modelled through the parameter **operational efficiency**, η, at month m and year y. This varies between 0 and 1 and is implemented by modifying the maximum potential power available to the project, shown in Equation 4.2. An operator with a low skill level (i.e. $\eta = 0.5$) will only be able to access one half of the available generation. The base operator conditions are shown in Table 4.5.

$$p[\hat{t}]_{y,m} = p[t]_{y,m} * \eta_{y,m} \tag{4.2}$$

The adjustment of operator skill level and corresponding available power generation is described in detail in Section 4.2.7. Operational Efficiency here represents the combination of factors which undermine the ability of the micro-utility to make use of the available power. This can be any number of issues: an inefficient charging process, poorly trained staff, insufficient marketing or poorly implemented sales efforts, poor inventory management, slow or improper maintenance activities, and others.

Operator skill level is directly related to the **decision speed**, γ. In the model, decisions allow the operator to make adjustments to key operating parameters on a regular basis – up to once per month for the highest skill level. Decision speed is set to match operational efficiency thresholds which assume that an operator with an ability

Table 4.5: Base Initial Operator Characteristics

Item	Value	Symbol	Range	Description
Operational Efficiency	0.8	η	$0.0 - 1.0$	Energy available after technical losses that can be used for project purposes
Decision Speed	3	γ	$1 - 4/mo$	Rate operational decisions are made

to achieve a higher operational efficiency will have the opportunity to make decisions at a faster rate.

Incorporation of a decision-making process that is regularly featured throughout the operational stage of a project is unique to sustainability modelling but has been argued in this thesis as a critical requirement for achieving the authenticity of real-world projects. It has been shown that many project receive considerable attention during the design stages, where modelers seek to represent the chaotic real-world with as much precision as possible. Once installed, projects will carry on, for better or for worse, with little attention to how decisions are made. However, there is a role for the operator's ability to adapt to the day-to-day state of the project to improve long-term performance of project, despite the limitations imposed by the design process. Speed of decision-making is therefore interpreted as the operator's ability to capture relevant indicators and put this information to action.

Initial **Decision Sets** are a ordered set of decision rules for a given operator. The decisions are classified according to the objectives: technical, economic, organisational, and social and are outlined in Table 4.6. They represent the rationales followed by the operator to make corrective decisions for the project. An operator may implement any combination of one or all decision sets. The detailed rules implemented for each decision sets are given in Section 4.2.7.

Decision priorities are established in the literature, but are rarely modelled. It is common to assume that the highest priority of a project is to achieve high reliability for example by minimising energy not served. Other priorities include maximisation of profits and maximization of impact outcomes. Decision priorities can be variable

Table 4.6: Operator Decision Sets

Decision Set Classification	Objective	Logic
Technical	Prioritises higher availability of private energy consumption (vs. public)	—if private availability is below requirement, decrease public target availability
Economic	Uses price mechanism to increase or decrease demand	—if current savings is below target then make adjustment, otherwise do nothing —if utilisation is high, than increase price (reduce demand) —if utilisation is low, decrease price (spur demand) —if utilisation is very high (> 95%), reduce public target availability (favouring private demand)
Social	Prioritises higher availability of public energy consumption (vs. private)	—if utilisation is high, decrease private availability target —if utilisation is low, increase public availability target
Organisational	Prioritises investment in training	—if current savings is above target (for the current month) AND utilisation is high, invest in training

depending on the context – stemming from objectives of the implementing organisation, sources of funding, and the operator's own approach. One project may emphasise impact in terms of maximising the number of users gaining access to electricity, while another may emphasise technical robustness, or in other words, may limit usage to ensure maximum reliability. Implementing organisations can implement training, or set operational guidelines, which an operator must follow. The designated decision priority may be overridden by an operator's own preference or even their own hidden priority such as increasing personal profits. Clearly, the selection of priorities is critical for the operation of the project and can have a enormous effect on sustainability. Unfortunately it is not clear in the literature which combination or order of priorities leads to the highest sustainability for a given context.

The **village market for electricity services** refers to the aggregation of all potential consumers; their combined demand and purchasing power for these services. Additionally it includes the responsiveness of the demand to changes in prices or levels of availability of supply to the public load. In this context, there is limited knowledge on the characteristics of local demand for several reasons. First, prediction of energy consumption through the use of field surveys has not proven to be accurate and suffers from unresolved methodological challenges [187]. Second, many projects will involve first-time access to the service and thus by definition no historical data actually exists. Third, similar and comparable projects tend to be poorly monitored, resulting in few data sources that could be used to build statistical models for predicting energy consumption at new locations. Therefore, it can be concluded that there is a gap in existing research around the estimation of new markets for electricity access in developing countries.

As the intention of the simulation is to incorporate an authentic demand response characteristic, the static load profile (as assumed in the reference model) are insufficient. The base load therefore is adjusted as the customer responds to specific signals as described in this section.

The modelled **load** consists of two electricity consumers. The first consumer represents an aggregation of all current paying customers, L_1, while the second consumer, L_2, is modelled as a public-service user, which, as a premise for undertaking a project, is given free electricity. In other words, the paying customers cross-subsidise the free energy for the public service user. This arrangement, while not universal, is nonetheless common and seen in several of the case studies. Although the specific nature of load for L_2 can in practice be many potential usages as it can represent a school, health facility, or community building; specifically it is modelled here as a small rural health post, matching the data-sets which are available for the simulation. Similarly L_1 is modelled specifically as customers using only a mobile phone charging service from a shared staff room within a primary school. Additional load types, both income generating and free, are not modelled for simplicity of the model.

First, the inherent demand for electricity for each consumer is initialised using real

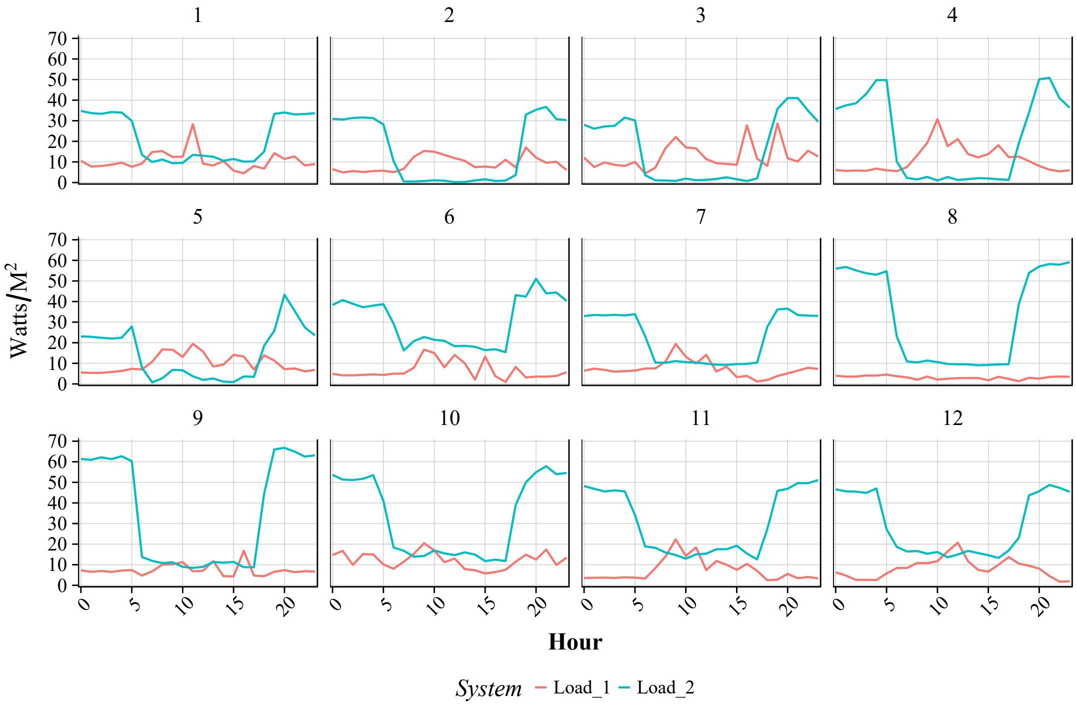

Figure 4.6: Base Load profile for each month at year 1

data from Malawi where over a year of hourly data was available for each consumer. Original data was gathered as part of the remote monitoring sub-programme for the Malawi Renewable Energy Acceleration Programme [168]. It should be recognised that additional error is reduced due to the availability of real data as opposed to survey-based or assumed demand profiles. In the case of application of the model during the design stage where no existing data-set is available, forecasted data would be substituted.

It is assumed that each consumer has a basic daily load profile as shown in the Figure 4.6. Each curve represents hourly loads for each data-set: paying (red) and public (blue) averaged over the course of each month. During the simulation the shape of the daily load profile does not vary within the month. To account for seasonality issues in the load profile, the daily load profile is updated for each month.

The demand L_2 is considered to be constant and inelastic to any pricing or supply changes which the operator may introduce. In the simulated scenarios, L_2 will always be free, and this customer will always take as much power as is supplied up to their full demand. This load represents a "free" social service offered as a condition of the project being established in a particular location. L_2 is thus only limited by what can be supplied by the project or any conscious decisions by the operator to increase or decrease availability of that supply. L_2 is assumed to only be served by the project and no other competitor.

Demand for the L_1 is a function of the price of energy, P as well as the proportion of fulfilled to unfulfilled supply provided to L_2: $L_{2,prop}$, as in Equation 4.3. This approach can be compared to the characterization of demand Louw et al. [188]. Equation 4.3 simplifies "tastes and preferences" to only consider L_f^{pub}, but does not model incomes of customers. Any influence income may have on demand for electricity is assumed to be exogenous and handled through the load growth parameter.

$$D_{L_1} = f\left[P, L_f^{pub}\right] \tag{4.3}$$

The literature defining a demand curve for electricity for new customer is not conclusive for consumers' first connections to a power supply in an off-grid setting. However, several resources along with direct data from a market study are used here to provide a basis for modelling.

A generic equation for the price elasticity of demand (PED) (shown in 4.4) relates the percentage change of quantity to the percentage change of price of a certain good. Several sources provide some initial insights in PED for electricity of demand for off-grid power supplies. PED appears to be context-specific and vary due to a number of factors such as time of year, whether long- or short- term, and demographics.

A study of own price elasticity of demand in Mozambique found a PED for rural households of -0.66 [3] corresponding to a 0.66% decrease in quantity of electricity damend for each 1% increase in price [189]. This study also found that PED was more inelastic, -0.49, for urban consumers indicating variation between stratas in the population. In [190], Filippinia and Pachauri conduct a regression analysis in India and find PED to vary between times of year: 0.416 (winter), –0.292 (summer), and 0.507 (monsoon). A study in Ethiopia used national consumption and expenses to estimate the costs of modern fuels for different segments of the population [191]. They found that

[3] these are expressed in %

households using electricity typically spent between 15% and 26% of their income on energy. PED for poor customers was found to be -0.75 (with a standard error of 0.287) and -0.77 (0.242) for the non-poor. Williams, Jaramillo, and Taneja use a triangular distribution of price elasticity of demand in their case study in Rwanda which ranged between -0.35 and -0.15 [192].

$$PED = \frac{dQ/Q}{dP/P} \tag{4.4}$$

An experimental study in Rwanda which implemented a bidding game for various solar product kits (ranging from 0.3 - 20Wp) to determine customer willingness-to-pay [193]. At each village a random price was drawn between the current market price (cap) and below and households which bid above the price were then offered the product at the drawn price. This approach was meant to solicit realistic bids which avoid strategic gaming scenarios. In figure 4.7 bids for the largest kit are shown. The aggregate market captured from lowering the price changes at different rates: a price adjustment of USD \$140 to \$120 confers a relatively small increase in customers, roughly %5 of the market, whilst an adjustment of \$120 to \$100 confers roughly 40% of the market.

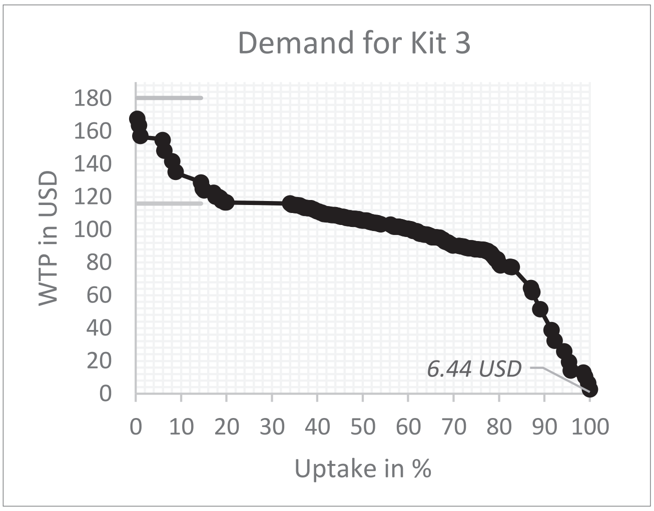

Figure 4.7: Individual Household Bids for A Solar Kit in a Rwanda Village

The results from a market assessment in Malawi provide additional insight [194].

Figure 4.8, which represents a combined estimate of yearly electricity expenditure in four un-electrified villages in Malawi. The Malawi data in the figure were gathered using a bespoke questionnaire as part of the Sustainable Off-Grid Electrification of Rural Villages (SOGERV) Project (*ibid.* Two methods are used to estimate potential energy expenditure, based on a method applied in Kenya [178]. The first method assumes 10% of yearly income will be spent on electricity (green curve). The second method assumes current energy expenditures can be fully substituted (blue curve). Given the variation between these two measures, an average of the two approaches is plotted alongside the approaches (red curve). In the figure, the points are ordered descending from the highest mid-point of expenses. Inspection of the curve shows that it is reasonable to expect as the price lowers, a higher share of participants will be able to participate in the market. For the entire data-set, the mean expense is 17,934 MWK (roughly USD $25 while the median expense is 10,100 MWK (roughly USD $13).

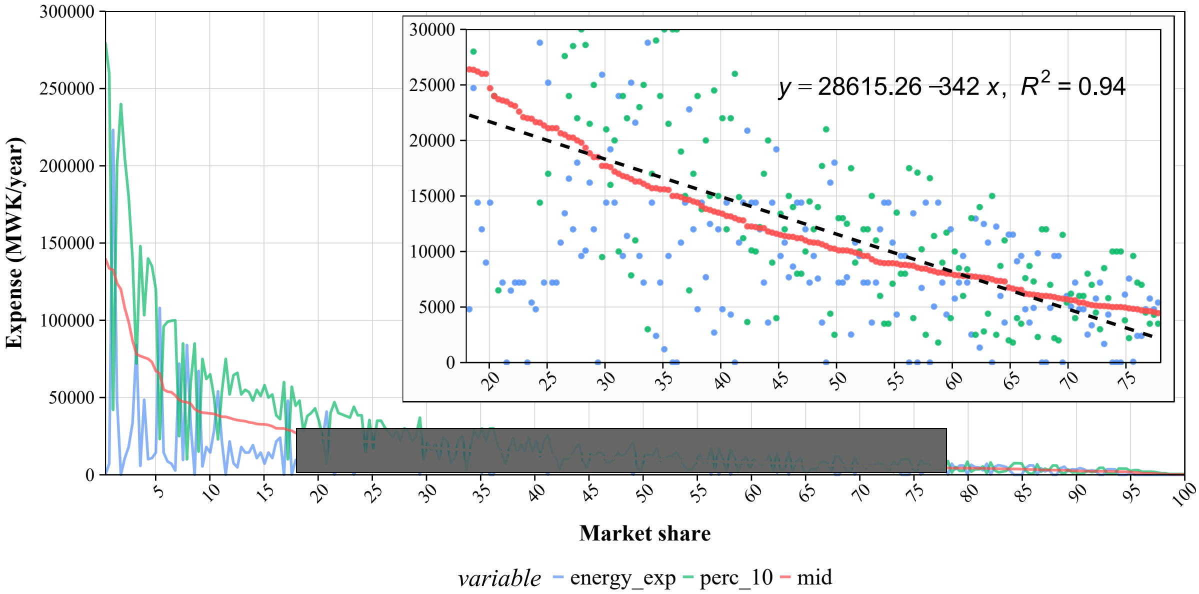

Figure 4.8: Market Share of Electricity Expenditure in 4 Malawi Villages

It can be observed that relatively higher spending users, for example over the range of 0 - 15% of the market, are more elastic than the majority of the market. Large price changes thus only capture a few percentage points of the market. In contrast for the vast majority of the market, highlighted in the second panel of the Figure covering 17%

- 77% of the market share, are much more responsive to price changes. Here a simple linear regression is modelled which provides a reasonable estimate of the demand in this range. For this range 1% price decrease is associated with a 1.195% increase in market share.

Hence the literature suggests that individual demand curves can be characterised as follows:

1. Demand for electricity can be considered a normal good, that is, it has a downward sloping demand curve and a negative PED.
2. For households with higher incomes, demand is more inelastic, less responsive to price changes
3. Variation exists for PED due to regional, seasonal, and demographic contexts
4. Typical PED found for off-grid electricity is between -0.66 and -0.75 with a standard error of around 0.25

PED is an important parameter in the simulation as it price adjustments are possible. A PED of -1.0 is in the base conditions though the impact of various PED levels is explored through a series of scenarios. The PED response for L_1 is handled as follows in Equations 4.5 and 4.6.

$$PED_{Adj} = D^*_{L1,y,m} \times (\frac{\hat{P}}{P_o} - 1) \times PED \tag{4.5}$$

$$\hat{D}_{L1,y,m} = D^*_{L1,y,m} + PED_{Adj} \tag{4.6}$$

Where $\hat{D}$ is the Demand at year y and month m for load L_1. $\hat{P}$ is the current price of electricity set by the operator and P_o is the design price. $\hat{P}$ can take any value $>= 0$. Load demand, as determined during design, is assumed to be known for P_o and is referred to as D^*. At $\hat{P} = 0$, demand is at its maximum and, in the base conditions, doubles the load demanded. It is assumed that the base load for each month has been estimated with perfect accuracy at P_o.

The **Social Demand Response** (SDR) provides a mechanism for social well-being to impact the electricity demand. It was noted in the literature review and case studies that the community's satisfaction in the project impacted their behaviour including their demand for electricity. This can be modelled with a demand 'reward' modifier, ρ, where high satisfaction increases demand, and a 'penalty' modifier, ϕ, that reduces demand when satisfaction is low. Splitting SDR into two separate parameters allows for the mutual existence of these effects and, furthermore, separate exploration in the sensitivity analysis. These effects are clearly context dependent, thus the inclusion of this aspect of the simulation can be considered optional. Intuitively, a SDR fits this context – in many projects a public provision of electricity is provided alongside a commercial aspect.

SDR is implemented by setting parameters for maximum reward and penalty as the case may be. Since each project may have different social context, some interpretation is needed to make them relevant. For example, in the Gambian case study (see Section 3), the provision of electricity to the primary school was argued to be linked to the private demand for electricity. In the model presented here, a high reward mechanism could be assumed. The reward and penalty mechanism of the social demand response is applied monthly, as shown in Equations 4.7 and 4.8. This can be interpreted as village consumers who are satisfied with the energy supplied to the health post respond by bringing a higher share of their business to the mobile phone charging scheme rather than to competitors. Equally, they may be more willing to travel further to charge their mobile phone even if they know it also benefits, in some way, the pupil's educational outcome. Conversely, a high penalty mechanism occurs when village consumers, due to low satisfaction with the electricity supply to the school, prefer not to use the scheme's mobile phone charging scheme and may travel further or even pay more to avoid it.

$$SD_{Adj} = \overset{-}{S}D + \left(\left(\frac{E^*_{L2,y,m-1}}{D^*_{L2,y,m-1}} \right) \times \left(\overset{+}{S}D - \overset{-}{S}D \right) \right) \tag{4.7}$$

$$\hat{D}_{L1,y,m} = D^*_{L1,y,m} \times SD_{Adj} \tag{4.8}$$

In the base simulation, a moderate reward, $\overset{+}{SD}$, and penalty, $\overset{-}{SD}$, term are arbitrarily set at 1.5 and 0.66 respectively, reflecting a range of potential demand adjustment of ±50%. During sensitivity testing, these terms are varied to explore settings where social demand may be stronger or weaker. In Equation 4.7, the proportion of energy served over the previous month of the free public load (given by $E^*_{L2,y,m-1}$) to total energy demand (given by $D^*_{L2,y,m-1}$) is used as a measure of the satisfaction of the service. The difference between reward and penalty variables set the response range. For example, if the previous month's proportion of energy supplied to energy demand for L_2 was 16.6% and the base social demand response terms (1.5 and 0.66) were used, then monthly load would be modified by a factor of 0.80.

The project's **system characteristics** are set at the initialisation stage and include an optimised system sizing, an initial design price of energy, and specific component characteristics. The simulation replicates the reference model system design described in Section 4.2.4 in order to have comparable technical results.

Additional assumptions that are set at initialisation are needed to handle decisions made monthly by the operator in the thesis model — at decision points. Recall that the operator makes adjustments to % target energy availability to each load, and % increase or decrease in energy prices charged to L_1. The level of adjustment at each decision point and is set from 2.25% to 6% in increments of 1.25% of the parameter in question, depending on the priority of the decision set. For example, in a month were the operator decides to adjust price of electricity, it will increase or decrease by ±6% of the current price if the economic decision set is ranked highest compared to other decision sets. This is meant to represent the operator making incremental improvements over time in the direction of an optimal decision, rather than assuming such an optimisation is immediately available[4]. Lower priority decisions adjust more slowly, allowing the higher priorities to dominate over time. The specific range was set as the model was validated — this allowed an operator to make relatively rapid decisions (6% change per month) for high priority decision sets.

[4]For example adjusting directly to price which would maximise income, or adjusting target availability to maximise demand

The initial targets for load availability for private load are set at 90% while the public load is set at 50%. These targets are adjusted throughout the simulation based on the operator decision set priority and used to determine conditional SDR. A specification of how these targets are used in the simulation are discussed in detail in the next section.

Since little numerical data exists on the training levels, impact of training and the link of training to operating performance, some assumptions are needed to implement a meaningful and representative, albeit initial, skills model. Operator skill level, ψ, handles both operational efficiency and decision speed. Decisions happen at discrete skill levels corresponding with operational skill level:

- $\Psi =< 0.7$, 1 decision point per 4 months
- $0.7 < \Psi <= 0.8$, 1 decision point per 3 months
- $0.8 < \Psi <= 0.9$, 1 decision point per 2 months
- $0.9 =< \Psi$, 1 decision point per 1 months

The level of investment needed for an operator to improve their decision speed to the next discrete level is equal to, cumulatively, 4 months of operating expense at the base conditions. An investment equal to 1 month of OPEX confers a 2.5% increase in operator skill level. Operator skill level is a continuous variable with range of 0 to 1. Operational efficiency, O_e, is equal to the operator skill level. Operator turnover and other means of skill attrition, are assumed not to be present. This component could be included to provide a more realistic representation of skill loss. Although the loss of an operator was experienced in the Muhuru Bay Micro Grid case study (see Section 3.2.2), the impacts of low skills are already captured by simulating scenarios which have a low initial skill base.

The model makes several general assumptions about the operating conditions of the project to limit the scope. It is assumed that system monitoring data is available and accessible to the operator as technical performance data such as utilisation rate and availability of supply are critical indicators used in decision-making. The replacement of broken equipment is assumed to be instantaneous, which simplifies delays that can occur during maintenance activities. A further extension of this research could include modeling the supply chain and incorporating a more realistic repair time to the components. Supply chain issues are a major challenge and many projects need to find the right balance between appropriate technology (as discussed in Chapter 3), which can be supplied more readily, and the technological sophistication. This feature is not included in the thesis model as the focus was at the high level financial sustainability operator decision making.

Input costs are assumed to be fixed and unchangeable throughout the simulation. Thus, reduced equipment costs over time, as production techniques improve and distribution is improved, do not affect the model, nor do cost savings activities affect operating expenses. Finally, although scaling-up of such projects are possible, the option is suppressed in the model, as sustainability of the original assets are the main concern of this research.

4.2.7 Operations Modules

The Operations modules of the simulation involve hourly calculations, primarily technical and economic in nature, as well as monthly decision points. For reference, the entire simulation is conducted for the desired time-span, assuming no operator decisions. Additional case studies are then specified where sensitivity parameters are varied and operator decision priorities are implemented. This section describe both the hourly and monthly resolution of calculations and decision-making.

Hourly Calculations

Energy generation, consumption and **battery energy levels** are resolved at an hourly increment. Simulation data from the initialisation modules provides multi-year data-sets for solar irradiance, temperature, and load as inputs and simulates solar panel generation and battery energy levels using the process described below. The control equipment is modelled as a charge controller that defines over-/under- charge protection limits to the net energy calculation. Unserved load and potential power generation are also calculated, corresponding to under-charge and over-charge protection controlling the net energy into the system respectively.

The potential power output of the solar modules per hour is calculated as shown in

Equation 4.9 generally following the method used in [109]. The equation corrects the power output depending on temperature differences from the standard test conditions using manufacturer provided correction coefficients [195], the actual panels used in the Malawi installations. The assumptions for panel and system losses are adapted from the guidelines in IEEE standards which specify a range of potential losses for each: wire losses, module mismatch, module aging, and dust and dirt [196]. The actual values shown in 4.1 have been chosen to be conservative as in [109].

$$p[t] = \frac{h[t]}{G_{STC}} \times \big(R_{PV} \times (\frac{P_{mp}}{100})\big) \times (T_C - T_{STC}) \times \prod 1 - L \qquad (4.9)$$

Where

- $p[t] = potential\, energy\, production,\ (Wh)$
- $h[t] = measured\, insolation\, at\, time\, t$
- $G_{STC} = insolation\, at\, standard\, test\, conditions\, for\, panel\, rating,\ (= 1000W/m^2)$
- $R_{PV} = PV\ Array\, rating,\ (W)$
- $P_{mp} = temperature\, correction\, factor\ (-0.45\, per\ 1°C)$
- $T_C = Adjusted\, Cell\, Temperature(°C)$
- $T_{STC} = Temperature\, at\, Standard\, Test\, Conditions\ (= 25°C)$
- $LS = vector\, of\, panel\, losses\ (S_1, S_2, S_3, S_4)$
- $S_1 = wire\, losses$
- $S_2 = module\, mismatch$
- $S_3 = module\, aging$
- $S_4 = dust\, and\, dirt$

Cell temperature is calculated in 4.10 using the Ross Co-efficient [197], k, which Skoplaki [198] reports as 0.0563 for PV systems on sloped roofs.

$$T_C = T_{amb} + k + E_e \qquad (4.10)$$

Where

- $T_C = Cell\, Temperature\ (C)$
- $T_{amb} = Ambient\, Temperature\ (C)$
- $k = Ross\, Coefficient$
- $E_e = Solar\ Radiation\ Flux\ on\ a\ Module\ Plane\ (W/m^2)$

Battery State of charge, SOC, ranges from 100% (fully charged) to 0% (fully discharged). A 100% charge corresponds to 1.224kWh of energy storage. Batteries are protected with a charge controller which ensure under and overcharge protection. The simulation assumes an undercharge protection set at 50% SOC where the batteries will be disconnected from the system. This is a common assumption for systems with lead acid batteries and is representative of the Malawi installed systems.

$$n[t] = p[t] - c[t] \tag{4.11}$$

$$\Delta b[t] = \begin{cases} n[t] \times \eta_{b,in} & n[t] > 0 \\ n[t] \times \eta_{b,out} & n[t] \leq 0 \end{cases} \tag{4.12}$$

$$b[t] = \begin{cases} b[t-1] & \begin{cases} b[t-1] + \Delta b[t] > R_B \times SOC_{H,t-1} \end{cases} \\ b[t-1] + \Delta b[t] & otherwise \end{cases} \tag{4.13}$$

$$b[t] = \begin{cases} R_B & b'[t] > R_B \\ R_B \times DOD & b'[t] < R_B \times DOD \\ b'[t] & otherwise \end{cases} \tag{4.14}$$

Where

- $n[t]$ = Net energy production, (Wh)
- $p[t]$ = Potential energy production, (Wh)
- $c[t]$ = electricity consumption at time t, (Wh)
- $\Delta b[t]$ = change in battery energy level at time t, (Wh)
- $\eta_{b,in}$, $\eta_{b,out}$ = Battery charging and discharging efficiency
- $b[t]$ = Battery Energy Level at time t, (Wh)
- $b'[t]$ = Battery Energy Level at time t after net energy applied, without limitation from DOD or R_B, (Wh)
- R_B = Battery Rating, (Wh)
- DOD = Battery Depth of Discharge Limit, %
- $SOC_{H,t-1}$ = Upper Charging Limit at time $t-1 = 0.98$

Net energy is calculated according to Equations eqs. (4.11) to (4.14), assuming an initial SOC of 95%. Advance charging algorithms such as a three-stage charge are not modelled. These could for example, confer different absorption characteristics over various SOC ranges. Instead it is assumed that the battery storage can absorb all energy charged up to a maximum of 100% SOC.

In the simulation, it is assumed that both private and public loads are prioritised equally during curtailment. Specifically, each load is curtailed according to its proportion to total load during the hour. When operator decisions occur, an availability target for both L_1 (private/paying load) and L_2 (public/free load) are set which determines the proportion of load served first. Targets are set as a percent of total demanded load. Further explanation of prioritisation of loads is described later in this Section. It is assumed that system load is served first by the panels and then by the batteries, if available, following the behaviour of most charge controllers. Additional PV output, beyond the load requirements, charge the battery, up to the capacity limits and according to the charge controller limitations already discussed.

Financial accounting occurs based on the technical system calculations. Revenues, expenses and subsequently the balance sheet which includes the profits and losses for the project are determined at every time step. For each hour, revenue is equal to the product of the current price of energy $\hat{P}$ set by the operator and the actual energy served. This arrangement is referred to as a flat energy rate tariff. According to the simulation assumptions, the energy which is actually sold only incorporates L_1, not L_2. The initial price of the energy is set by the reference model determined by levelised cost of energy for the system and adjusted to account for non-paying load which is 47.1% of initial energy consumption.

Operating expenses (OPEX) are assumed to be fixed and equal to a proportion (10%) of the initial project capital expense (CAPEX) per year. For the simulated system, this is equal to $548.20 per year. Since there is no fuel costs, the bulk of this OPEX is assumed to be related to salaries and logistical costs (such as transport) of operating the project. This value is consistent with the projects highlighted in the case studies. OPEX is applied on an hourly basis for the purposes of financial accounting. For the case of a renewable only system in this context, a fixed OPEX cost is sufficient for modelling, consisting mainly of labour expenses.

CAPEX costs are based on the component sizes determined in Section 4.2.4 and known component prices in Malawi in 2015 and are detailed in Table 4.1. Louie and Dauenhauer develop a linear cost model relating panel and battery sizes to expected costs [109]. Additionally, comparison of major component costs (panels, batteries, converters, installation, and other costs) from 10 projects completed in MREAP are used to estimate the remaining initial CAPEX. Since costs vary from one country to the next and CAPEX for distributed renewable systems continues to decrease, modelled costs could be adjusted to other contexts as appropriate. In comparison with the literature, the cost estimates are comparable to other projects in an off-grid setting in developing countries [199–201].

Monthly Calculations

As the simulation progresses, the **component breakage schedule** is referenced and resolved if a failure occurs. It is assumed that all failures result in full system shutdown for simplicity, though in practice ad-hoc 'repairs' allow for some level of functionality. Equally it is possible for the system to run while derated, for example individual battery or panel failure. Replacements are made instantaneously do not impact technical operation. The financial impact of replacement is recorded using the original component costs (see Table 4.1). An improvement could seek to model the costs associated with utilising a supply chain for parts and service which would result in longer downtime. Unfortunately, there was little support in the literature to model the timing and complexities of the interaction with supply chains.

Operational Efficiency is updated monthly according to the current operator skill level and level of investment. In some cases, no investment will occur and operational efficiency will be inherited from the previous month. In scenarios where operator decisions are included, operational efficiency will grow naturally at a slow rate, as a learning-by-doing process plays out.

Several **indicators** are recorded monthly basis and serve as the main information used for decision-making. Indicators are project-centric following the approach outlined in Chapter 2. Additionally, the same indicators are reported to conduct the sustainability analysis.

Public and Private Availability, Θ, is the proportion of energy supplied to energy demanded over the last full month of service. For the availability for the paying customer this is calculated by dividing the energy supplied, $\overline{S}_{L1}$, by the total energy demanded, D_{L1}, as shown in Equation 4.15. Since operator decision and customer responses vary dynamically throughout the simulation, a minimum availability of supply is not included. Higher availability for L_1 corresponds with higher technical performance, since revenues are generated from the energy sold to L_1, it has direct impact on the financial position of the project. Availability of the non-paying public load, L_2, is calculated similarly, confers no direct revenue, but can impact market through the SDR mechanism.

$$\Theta_{L1,y,m} = (\sum_{m-1}^{m} \overline{S}_{L1,y})/(\sum_{m-1}^{m} D_{L1,y}) \tag{4.15}$$

Utilisation factor, κ_u is the proportion of energy consumed to the maximum potential energy generated on the system for the previous month, shown in Equation 4.16. Utilisation factor is important as when it is below 100%, it indicates that there is unused energy generation that could otherwise be sold or directed to the public load. This instance occurs either when there are daily temporal imbalances in supply and demand, overall low demand, or system over-sizing. Due to seasonal and daily trends in load and resource availability, a constant utilisation factor is not likely. Since the load and weather characteristics are known during system sizing, an optimal design with relatively high utilisation has been selected. Additionally, a high utilisation can also be important for identifying when the system is reaching its capacity: a period where there is unserved load can nonetheless utilise all available energy generated.

$$\kappa_{u,y,m} = (\sum_{m-1}^{m} \overline{S}_{L1,y} + \overline{S}_{L2,y})/(\sum_{m-1}^{m} p[t]) \tag{4.16}$$

The **savings target**, Sav is an averaged monthly monetary value needed to cover long-term asset (CAPEX) costs, shown in Equation 4.17. The savings target is a critical indicator as failure to achieve sufficient savings will prevent the ability to replace failed components and inhibit or totally cease project operations. Depreciation is applied to each major component over their expected life-cycle (see Table 4.1 for details) with a simple linear model. Averaged monthly PV depreciation is given by PV_m referring to a CAPEX of $420 over 20 years, or, a monthly cost of $1.75. Batteries and inverters are notated similarly. Since breakdowns are generated according to a probabilistic schedule, the savings target needs to be updated whenever a breakdown occurs or the component is fully depreciated. Each instance of equipment which fails before expectation results in sunk costs, denoted with subscript $_{sunk}$. For simplicity, an average monthly sunk cost for each component accounted for using the same depreciation schedule. Hence, a component that fails on July 1st, 3 months prior to its schedule end of depreciation date will only be fully accounted for on October 1st.

$$Sav_m = \big(PV_m + BAT_m + INV_m\big) + \big(PV_{m,sunk} + BAT_{m,sunk} + INV_{m,sunk}\big) \quad (4.17)$$

Monthly Operator Decisions

The simulation provides a framework for implementing decision sets for an operator of the project with 4 main themes: technical, economic, social, and organisational. An environmental decision set is not included as it did not appear in the literature review in Section 3.1. Each priority is modelled separately to explore the implications of single or combinations of decisions on the outcome of the project.

The **technical decision-making** theme prioritises a high level of availability of L_1, the paid customers at the expense of the level of availability of L_2, the public load. The target availability for both loads are initially set at 90% with an acceptable range of allowing +/- 2.5%. If $\Theta_{L1,y,m-1}$ is less than the target availability, then the operator will reduce availability target to public load. If $\Theta_{L1,y,m}$ is greater than the target availability, then the operator will increase the availability target to the public load.

The **economic decision-making** theme prioritises the project's financial performance and in particular, meeting the savings target of the project. As long the monthly savings target is met, no change is made by the operator. If the savings target is not met, the operator evaluates the preferred way forward through the utilisation factor and by attempting to adjust the load demand. If utilisation is low, the simulation considers this as less than 75%, then there is insufficient demand for energy. As a result, the operator decreases prices to stimulate demand. Conversely, if the utilisation is high, i.e. greater than 90%, the price is increased to increase revenue per customer. Additionally, target availability for L_1 is increased (to a maximum of 100%) – this increases the share of electricity which goes towards L_1.

The **social decision-making** theme priorities a high level of availability to L_2, the public customer at the expense of availability of supply to L_1. If the current utilisation is high (over 90%), then little additional, unused, capacity is available for L_2, and the availability target for L_1 is decreased to increase the share of electricity which goes towards L_2. If the current utilisation is low (less than 75%), then unused capacity can be used for L_2. In this case the operator increases the target availability to L_2.

Finally, the **organisational decision-making** theme prioritises training for the operator, effectively increasing operational efficiency and decision speed. It is assumed that a steady improvement in operator skill occurs from experience on the job, or in other words, learning by doing. For each decision point, efficiency is improved by 0.25%. In addition to this effect, the operator will invest if the savings target is being met and utilisation factor is considered high (over 90%). During this instance, a proportion of monthly savings is diverted to a training budget. It is assumed that the training budget is spent instantaneously and, as a result, improves the operator skill level, Ψ. The operator skill level corresponds directly to operational efficiency, both variables have a range of $0 - 1$. A training investment equivalent to one month of OPEX confers a 10% skill level increase, to a maximum of 1. Once the operator reaches 100% skill level, there is no further investment. Retention of the operator is not modelled. Decision speed is adjusted at discrete levels as described in Section 4.2.6.

The **level of adjustment per decision point** ranges from 2.25% to 6%. The exact level is dependent on the order of the decision-making, or in other words, in descending strength to the priority. For the operator, it is possible to assign one or a combination of decisions corresponding with the themes described previously. Hence, if 'technical' is the first (or only) priority, the operator will adjust, the availability target by the highest level of ±6% per decision point when the specified conditions are met. A second priority, for example, 'economic', would then adjust the price by only ±4.75% if conditions were met. Third and fourth priorities are further reduced in level of adjustment to ±3.5% and ±2.25%, respectively. The organisational adjustment is handled slightly differently than the other themes: the level of investment in training, when conditions are met, is equal to 100% of monthly profits if it is the first priority, dropping to 75% if it is second priority, and so on. The exact % adjustment is arbitrary and was set during the validation of the model to reflect incremental decision-making, yet decision that are significant to make a difference in the outcomes.

The decision-making is unique in that it emulates dynamic and iterative decisions that could feasibly be made by a real operator throughout the life-cycle of the project. It is often the case that the multiple objectives of any given project (economic, technical, social, organisational) cannot be achieved at all times or have will conflicting roles. The level of adjustment is small and does not, instantaneously, choose the optimal set points for the project. By design, the compounding effect of decisions made over time will converge upon these optimal set points according to the priority of the operator. Higher priorities, which have larger adjustments will tend to have a stronger effect on the actions taken.

Although the simulation can generate a random breakdown scenario, a single set is generated and used exclusively to provide a comparable analysis between scenarios. Breakdowns for each component is shown in Table 4.7. Note that as the schedule for breakdowns extends beyond the simulation time-span, not all breakdowns will actually occur in the simulation.

Table 4.7: Months of operation until breakdown for all major components, from inception or last breakdown

Instance	Converter	PV	Batteries
1	76	192	13
2	103	194	36
3	383	670	28
4	215	203	15
5	321	281	53
6	295	922	34
7	566	124	54
8	3	199	68
9	4	43	25
10	187	54	35

4.3 Model Validation

To validate the technical system model, a simplified scenario is run and compared against a techno-economic optimisation platform output. This reference simulation, using the HOMER system model described previously, and used in initial system sizing serves as a comparison case. The following technical parameters are compared: PV output, load demand served, battery state of charge, and expenses. Since the reference simulation synthesises these inputs, even if time-series data-sets were provided (as here), it is necessary to compare the input to synthesized data as well.

4.3.1 Input Data Comparison

The reference model does not incorporate load growth or demand adjustment effects (namely: PED and SDR) and hence has only one year of data which is used to initialise a data-set for the entire period of interest. Input consumption is compared against the reference mode daily consumption in kWh as shown in Figure 4.9. For the most part, synthesised consumption data closely follows the input data except for the second half of October where daily consumption is slightly reduced.

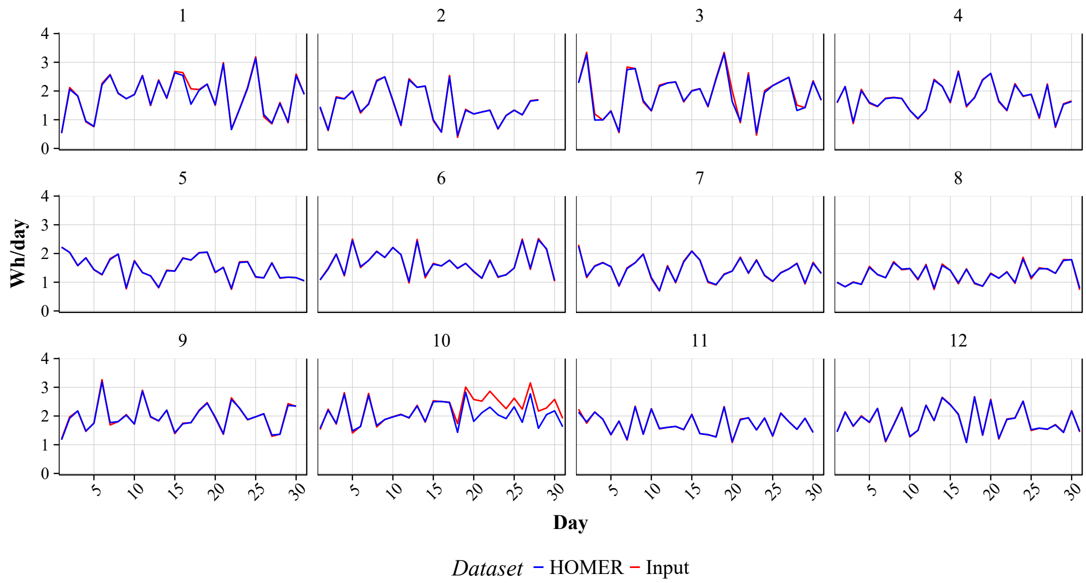

Figure 4.9: Comparison of Input Consumption Per Day, kWh

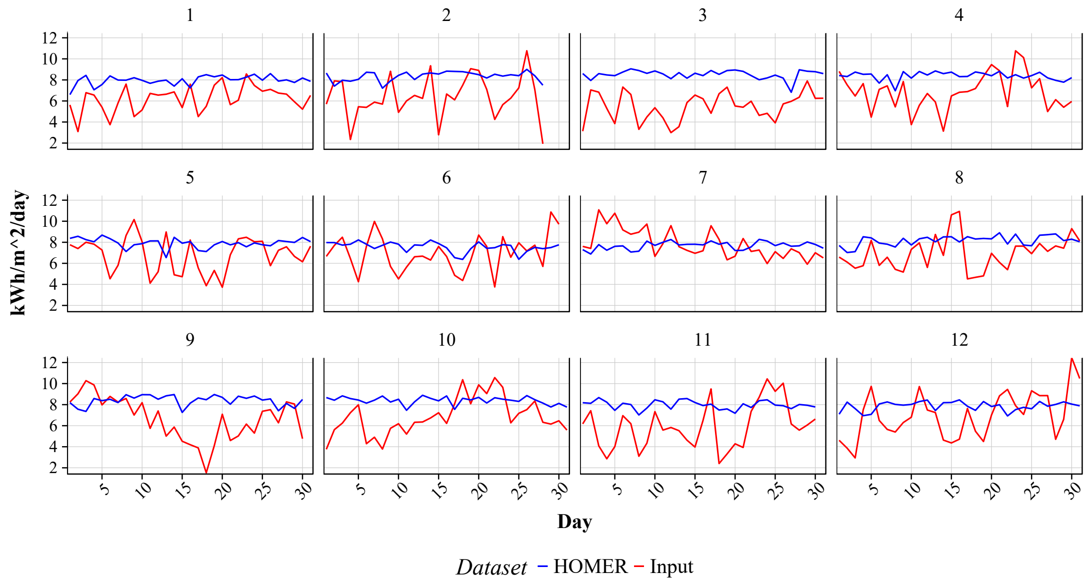

Figure 4.10: Comparison of Input Daily Solar Irradiation, kWh/m^2/day

Handling of irradiance is shown in 4.10 with the input data plotted as the red curve and reference simulation data as the blue curve. Mean daily irradiance for the reference model data-set is 8.1 kWh/m^2 ($\sigma = 0.52$) compared to 6.67 kWh/m^2 ($\sigma = 1.84$) for the input data-set. Clearly the reference model significantly reduces the day to day variance and has raised mean daily irradiance. It is sufficient that the thesis model mean daily irradiance is within 1 standard deviation of the reference model.

4.3.2 Results Comparison: thesis model versus reference model

This section compares the reference model output to simulation output. For the simulation the year 2023 is selected by finding the year which is most comparable, in terms of yearly irradiance and consumption, to the reference model synthesised data. For reference the overall difference in irradiance over the year was -384.9 kWh/M^2 with the simulated data less than the reference model data and the consumption difference was 1.6 kWh.

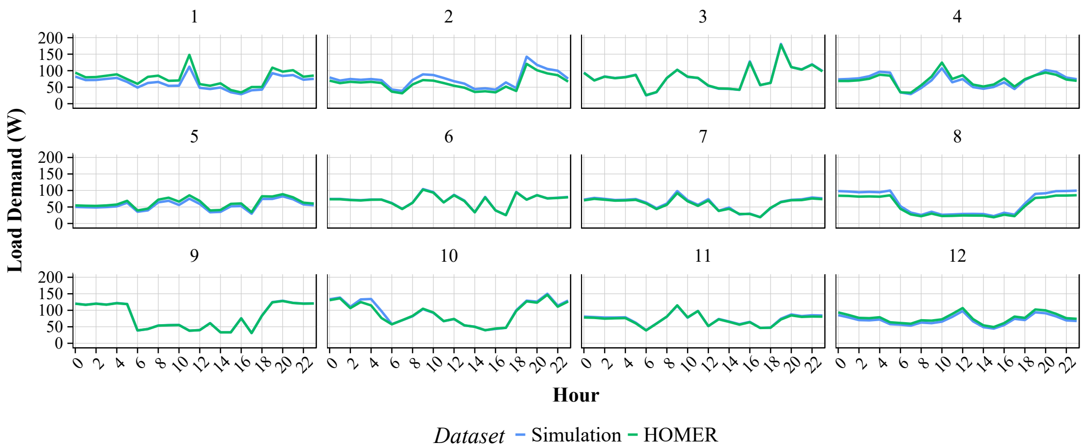

Figure 4.11: Comparison of Daily Consumption, Simulated vs HOMER, Wh

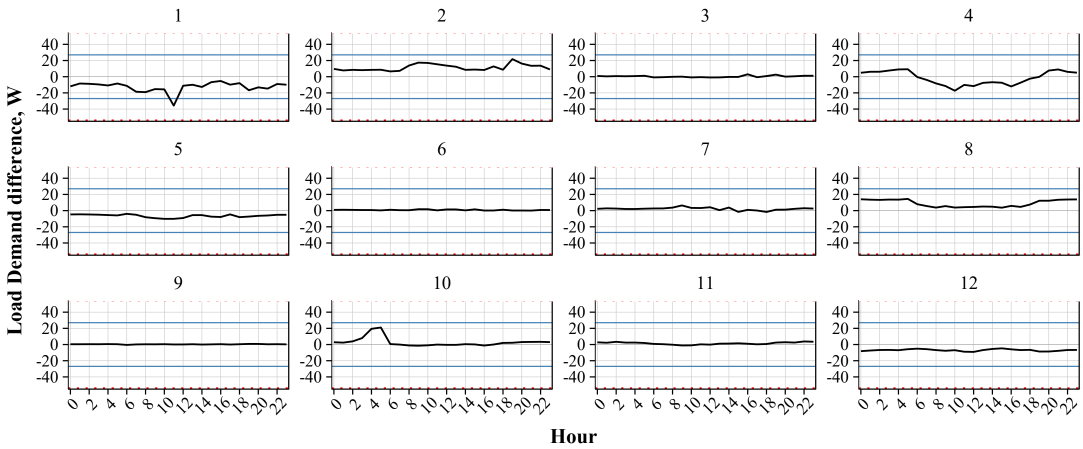

Figure 4.12: Difference in Daily Consumption, Simulated vs HOMER, Wh

Figures 4.11 and 4.12 show the daily consumption profiles over the course of the year and the hour by hour difference between the simulated and reference simulation results, respectively. The horizontal lines are placed for readability; the blue lines on the hourly profile are ±25 while the red lines are ±50. It can be observed that the load profiles are nearly identical, differing usually by less than 20W at any given time.

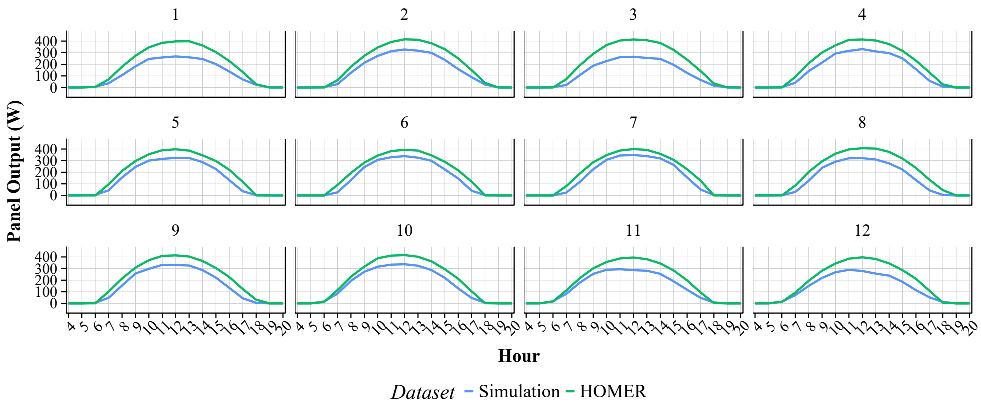

Figure 4.13: Comparison of Power Production, W

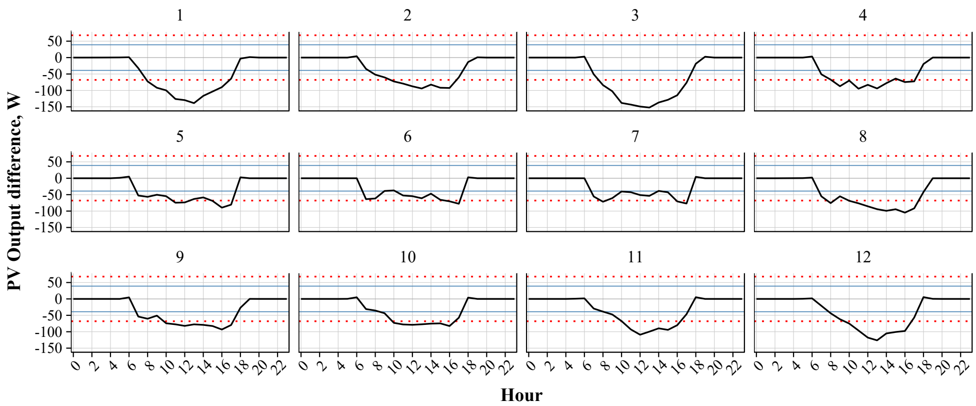

Figure 4.14: Difference in PV Output, W

PV output is shown in Figure 4.13 where the blue curve represents thesis model values while the green curve is reference model values. The difference in PV output is shown in Figure 4.14 with error bounds of 5% (or 39W, solid blue lines) and 10% (or 68W, dashed red lines) of rated PV capacity. The main pattern which emerges is that the reference model PV output exceeds simulated output, due to the higher levels of irradiation from data synthesis. While most months approach the lower 10% error bound, 5 months exceed this significantly with a maximum difference of 150W in March (∼22%). While not ideal, the result is consistent with the synthesised data.

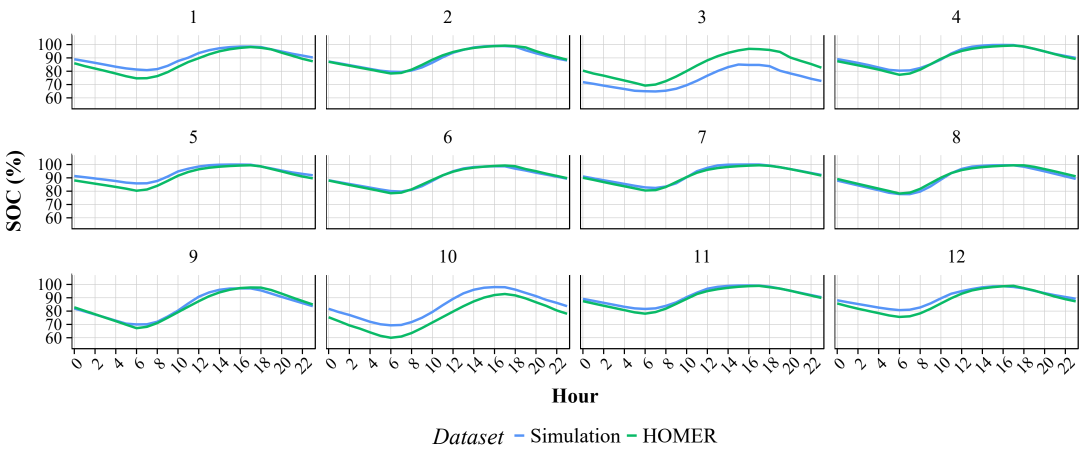

Figure 4.15: Comparison of Battery State of Charge, W

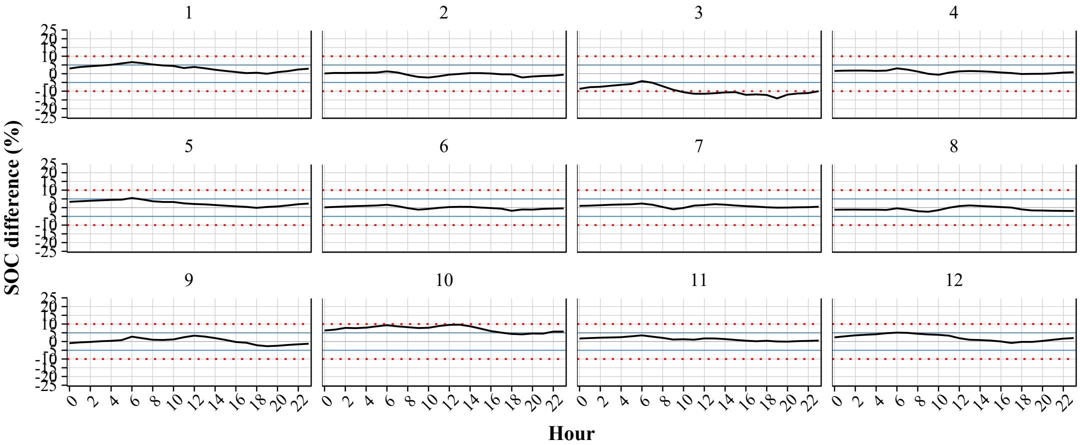

Figure 4.16: Difference of Battery State of Charge, W

A comparison battery State of Charge (SOC) is shown in Figure 4.15 with differences plotted in Figure 4.16. Error bounds of 5% (solid blue lines) and 10% (dashed red lines) are also plotted. The minimum SOC is 50%, determined by the charge controller protection setting. Differences in SOC are less than 5% in all months except for March and October. In March, the lower simulation SOC is due to a large discrepancy in irradiance and resulting in much lower PV output for the simulated data (see Figure 4.14). October has the highest overall consumption of all months. Detailed inspection of October found a series of evenings with relatively high consumption in the reference simulation which could not be recovered without failing to meet some load, primarily during the second half the month. In the simulated data, this period happens to have some low load days where the battery SOC could respond.

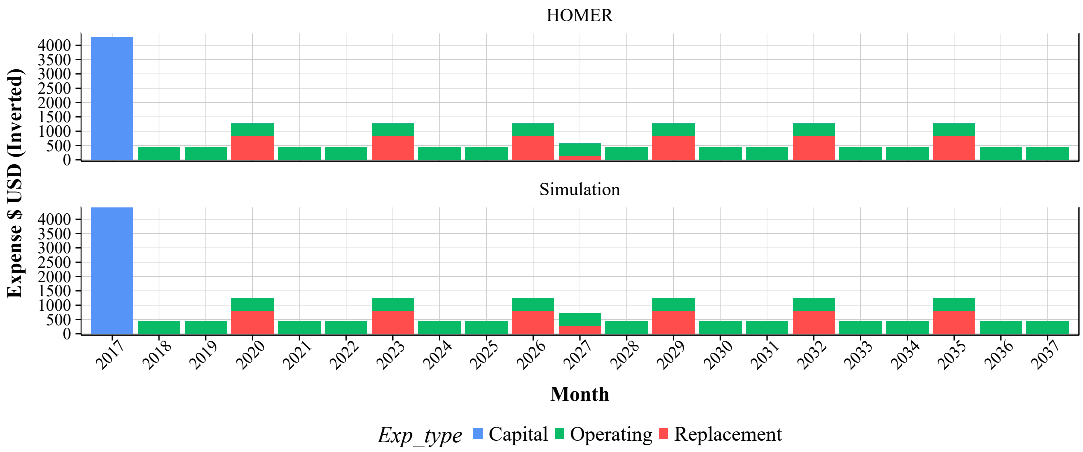

Figure 4.17: Comparison of expenses, $ USD

Figure 4.17 compares the expense structure of the simulation for each major expense type: initial capital, replacement costs, and operating expenses. As is clear, the cost structure is almost identical.

4.3.3 Validation Conclusions

This section has compared the technical and economic performance of the simulated model versus the reference simulation. Difference in data synthesis techniques explained much of the variation in the model results, however overall, these were reasonable similar to one another. In particular, the reference model's interpretation of irradiance input values increased the mean daily irradiance resulting in higher PV output when compared to the simulation results. Despite these differences, battery SOC, which inherently is affected by differences in irradiance (and hence PV output) as well as the load profile, matched reasonably well. Two months where SOC was outside the 10% error bounds were investigated more closely and found to be artefacts of the data synthesis. As a result of the validation, further simulation pursued in later sections can be considered to produce reasonably comparable techno-economic results to the reference model.

4.4 Analysis and Results

This section presents the analysis and results of 23 individual sustainability simulations. The analysis considers scenarios with varying complexity from the base scenario where no decision-making takes place to scenarios involving multiple operator decisions and varying levels of social demand response and initial operator skill levels.

Scenario Descriptions

The scenarios are outlined in Table 4.8. They are selected in order to explore the implications of the choice of decisions, priorities of decision, and to conduct a sensitivity analysis. The sensitivity analysis is completed in order to identify base parameters which do not dominate the results and include initial operator skill levels, level of social demand response, and price elasticity of demand. These themes also serve to organise the comparison of the results, which follow in the next section.

The analysis begins with the single decision scenarios #1 - #5, then presents scenarios including a sensitivity analysis (involving adjustment of Social Demand Response #11 - #14, Operator Skills #15 - #18, and Price Elasticity of Demand #19 - #23), and concludes with scenarios involving all four decision sets #6 - #10. The section concludes by discussing the model's implications for sustainability and considerations around the modelling approach.

Table 4.8: Scenario Specification

No.	Name	Decision Order	PED	Social Demand Response		Init. Operator Skill level	
				$\overset{+}{SD}$	$\overset{-}{SD}$	ψ	Ψ
1	Base	(None)	-1.5	1.5	0.66	0.8	3
2	Tech-only	Tech	-1.5	1.5	0.66	0.8	3
3	Econ-only	Econ	-1.5	1.5	0.66	0.8	3
4	Soc-only	Soc	-1.5	1.5	0.66	0.8	3
5	Org-only	Org	-1.5	1.5	0.66	0.8	3
6	"OSET", Org Top	Org, Soc, Econ, Tech	-1.5	1.5	0.66	0.8	3
7	"SOET", Econ Top	Soc, Org, Econ, Tech	-1.5	1.5	0.66	0.8	3
8	"EOST", Soc Top	Econ, Org, Soc, Tech	-1.5	1.5	0.66	0.8	3
9	"TOSE", Tech Top	Tech, Org, Soc, Econ	-1.5	1.5	0.66	0.8	3
10	"TESO", Reverse Order	Tech, Econ, Soc, Org	-1.5	1.5	0.66	0.8	3
11	No Soc Dem Resp	Soc	-1.5	1.00	1.00	0.8	3
12	Soc - High Penalty	Soc	-1.5	1.00	0.50	0.8	3
13	Soc - High Reward	Soc	-1.5	2.00	1.00	0.8	3
14	Soc - High Both	Soc	-1.5	2.00	0.50	0.8	3
15	Skill - High Initial	Org	-1.5	1.5	0.66	0.95	1
16	Skill - Medium Initial	Org	-1.5	1.5	0.66	0.9	2
17	Skill - Low Initial	Org	-1.5	1.5	0.66	0.80	3
18	Skill - Very Low Initial	Org	-1.5	1.5	0.66	0.70	4
19	PED Very High	Econ	-2.0	1.5	0.66	0.8	3
20	PED High	Econ	-1.5	1.5	0.66	0.8	3
21	PED Medium	Econ	-1.0	1.5	0.66	0.8	3
22	PED Low	Econ	-0.5	1.5	0.66	0.8	3
23	PED Very Low	Econ	-0.25	1.5	0.66	0.8	3

Tabular Results

For convenience, the results of the simulations are produced at the start of the analysis. Critical metrics are reported on years 1, 5, 10, 15, and 20 (the end of the simulation) and shown in tabular format in Tables 4.9 through 4.12.

- financial performance (cumulative project balance)
- technical performance (availability of service to private customer, total energy served)
- Operating efficiency
- social performance (availability of service to health post)

Table 4.9: Project Balance, ($USD), on year (1,5,10,15,20).

Simulation	No	2017	2021	2026	2031	2036
Base	1	-4,251	-4,325	-3,463	-887	1,522
Tech	2	-4,251	-4,325	-3,511	-1,072	1,377
Econ	3	-4,251	-4,278	-3,398	-1,050	908
Soc	4	-4,250	-4,063	-2,727	-376	1,173
Org	5	-4,251	-4,325	-3,542	-1,159	2,164
OSET	6	-4,248	-4,053	-2,706	23	1,866
SOET	7	-4,248	-3,912	-2,695	-484	-179
EOST	8	-4,249	-3,915	-2,771	275	3,620
TOSE	9	-4,249	-3,919	-2,745	-360	2,128
TESO	10	-4,249	-3,920	-2,665	-165	2,382
No SDR	11	-4,280	-4,599	-4,173	-2,394	-1,041
High Reward	12	-4,107	-2,860	-630	2,369	4,332
High Penalty	13	-4,370	-5,275	-5,202	-3,727	-2,843
High Both	14	-4,187	-3,402	-1,473	1,248	2,979
High Skill	18	-4,251	-4,330	-3,393	-344	3,008
Medium Skill	19	-4,251	-4,324	-3,499	-453	2,892
Low Skill	20	-4,251	-4,325	-3,542	-1,159	2,164
Very Low Skill	21	-4,251	-4,334	-3,619	-1,408	431
Very High PED	25	-4,251	-4,223	-3,201	-693	1,387
High PED	26	-4,251	-4,278	-3,398	-1,050	908
Med PED	27	-4,251	-4,335	-3,629	-1,460	356
Low PED	28	-4,252	-4,400	-3,868	-1,883	-175
Very Low PED	29	-4,252	-4,432	-3,993	-2,102	-462

Table 4.10: Public (Free) Load Not Served, Total kWh, on year (1,5,10,15,20).

simulation	No	2017	2021	2026	2031	2036
Base	1	0	0.9	4.6	34.1	71.8
Tech	2	0	0.9	2.8	12.3	13
Econ	3	0	1.5	9.2	50.1	93.1
Soc	4	0	7.7	63.3	191.1	280.5
Org	5	0	0.9	3.7	15	35.7
OSET	6	0	15.2	12.4	19.1	15.6
SOET	7	0	22.8	18.4	24.8	28.1
EOST	8	0	15.3	43.3	14.7	8
TOSE	9	0	12.5	16.6	13.7	6.5
TESO	10	0	12.4	18.4	16	5.8
No SDR	11	0	2.1	37.2	168.2	267.9
High Reward	12	1.2	19.9	82.9	235.1	327.4
High Penalty	13	0	1.4	33.2	140.7	227.1
High Both	14	0	15.4	78.7	211.4	296.6
High Skill	18	0	0	0.9	14.3	33.9
Med Skill	19	0	0.1	0.9	14.3	34.6
Low Skill	20	0	0.9	3.7	15	35.7
Very Low Skill	21	0	2.1	9.3	50.5	90.4
Very High PED	25	0	1.8	10.4	53.5	98.1
High PED	26	0	1.5	9.2	50.1	93.1
Med PED	27	0	1.4	7.9	45.4	87.6
Low PED	28	0	1.1	5.9	39.8	79.9
Very Low PED	29	0	1	5.2	36.9	76.2

Table 4.11: Private (Paying) Load Not Served, Total kWh/yr, on year (1,5,10,15,20).

simulation	No	2017	2021	2026	2031	2036
Base	1	0	1.8	11.8	70.8	105.4
Tech	2	0	1.8	7.8	43.7	40.3
Econ	3	0	3.3	28.9	113.4	160.5
Soc	4	0	11.8	66	167.3	221
Org	5	0	1.7	9.5	42.1	60.9
OSET	6	0	21.3	20	29	14.2
SOET	7	0	30.7	22.4	16.5	4.7
EOST	8	0	21.6	55	48.4	28.4
TOSE	9	0	19.6	34.3	44.2	18
TESO	10	0	19.5	36.2	54.9	25.6
No SDR	11	0	2.7	30	123.3	194.3
High Reward	12	3.9	41.2	118.9	276.3	368.9
High Penalty	13	0	1.6	23	86.2	119.4
High Both	14	0	29.1	96.2	213.3	273.4
High Skill	18	0	0	3.2	40.3	59.1
Med Skill	19	0	0.3	3.2	40.5	59.8
Low Skill	20	0	1.7	9.5	42.1	60.9
Very Low Skill	21	0	4.3	24.1	92.3	127.8
Very High PED	25	0	4.3	33	122.7	174.5
High PED	26	0	3.3	28.9	113.4	160.5
Med PED	27	0	3	24.2	100.6	143.8
Low PED	28	0	2.4	17.3	85.9	124.4
Very Low PED	29	0	2	14.4	78.7	115.2

Table 4.12: Operating Efficiency, %, on year (1,5,10,15,20).

simulation	No	2017	2021	2026	2031	2036
Base	1	80	80	80	80	80
Tech	2	80	80	80	80	80
Econ	3	80	80	80	80	80
Soc	4	80	80	80	80	80
Org	5	80.1	80.7	83.7	100	100
OSET	6	80.1	85.5	100	100	100
SOET	7	80.1	84.1	99.9	100	100
EOST	8	80.1	80.7	87.2	100	100
TOSE	9	80.1	80.7	84.4	100	100
TESO	10	80.1	80.7	82.6	87.7	100
No SDR	11	80	80	80	80	80
High Reward	12	80	80	80	80	80
High Penalty	13	80	80	80	80	80
High Both	14	80	80	80	80	80
org_soc	17	80.1	81.1	96.4	100	100
High Skill	18	95.2	98.1	100	100	100
Med Skill	19	90.1	91.2	100	100	100
Low Skill	20	80.1	80.7	83.7	100	100
Very Low Skill	21	70	70.5	71	71.5	72.1
Very High PED	25	80	80	80	80	80
High PED	26	80	80	80	80	80
Med PED	27	80	80	80	80	80
Low PED	28	80	80	80	80	80
Very Low PED	29	80	80	80	80	80

Table 4.13: Public (Free) Load Served, kWh, at year (1,2,3,4,5,10,15,20)

simulation	No	2017	2021	2026	2031	2036
Base	1	111.1	134.7	171.2	190.3	201.8
Tech	2	111.1	134.2	154.0	151.6	132.5
Econ	3	111.1	134.2	166.6	174.4	180.6
Soc	4	114.9	187.1	259.9	256.7	265.6
Org	5	111.1	134.8	172.1	209.4	237.9
OSET	6	119.3	214.5	273.5	280.7	308.3
SOET	7	121.5	226.3	295.3	351.4	480.3
EOST	8	117.1	200.9	256.1	182.7	131.5
TOSE	9	117.1	195.1	210.9	184.1	156.5
TESO	10	117.1	195.1	209.1	167.1	105.9
No SDR	11	114.9	197.1	293.3	279.6	278.3
High Reward	12	113.7	166.6	214.2	212.8	218.7
High Penalty	13	114.9	197.8	304.7	307.2	319.0
High Both	14	114.9	175.1	232.0	236.5	249.5
High Skill	18	111.1	135.7	174.9	210.2	239.7
Med Skill	19	111.1	135.5	174.9	210.1	239.0
Low Skill	20	111.1	134.8	172.1	209.4	237.9
Very Low Skill	21	111.1	133.6	166.5	174.0	183.2
Very High PED	25	111.1	133.9	165.4	170.9	175.5
High PED	26	111.1	134.2	166.6	174.4	180.6
Med PED	27	111.1	134.3	167.9	179.1	186.0
Low PED	28	111.1	134.6	169.9	184.6	193.7
Very Low PED	29	111.1	134.7	170.6	187.6	197.4

Table 4.14: Private (Paying) Load Served, kWh, at year (1,2,3,4,5,10,15,20)

simulation	No	2017	2021	2026	2031	2036
Base	1	232.6	273.4	340.5	363.1	404.3
Tech	2	232.6	273.2	331.9	358.9	415.7
Econ	3	233.9	297.2	380.9	387.7	424.1
Soc	4	234.5	304.5	356.0	321.2	340.7
Org	5	232.6	273.6	343.6	406.3	479.0
OSET	6	238.0	339.3	380.8	342.7	334.7
SOET	7	239.1	340.5	371.2	271.3	168.2
EOST	8	236.8	327.6	393.7	422.4	485.2
TOSE	9	236.9	325.6	386.2	412.8	445.1
TESO	10	236.9	325.2	382.1	399.5	494.0
No SDR	11	215.4	252.8	301.1	303.1	333.2
High Reward	12	319.7	373.1	406.5	347.7	363.5
High Penalty	13	162.9	218.7	286.8	278.5	300.1
High Both	14	272.5	348.6	390.3	334.8	347.5
High Skill	18	232.6	275.8	353.0	408.7	481.7
Med Skill	19	232.6	275.4	353.0	408.4	480.7
Low Skill	20	232.6	273.6	343.6	406.3	479.0
Very Low Skill	21	232.6	270.2	323.4	329.8	366.1
Very High PED	25	234.3	304.6	389.4	392.8	426.3
High PED	26	233.9	297.2	380.9	387.7	424.1
Med PED	27	233.4	291.7	369.9	382.5	420.0
Low PED	28	233.0	282.6	356.4	373.0	412.4
Very Low PED	29	232.8	278.1	348.8	367.9	407.7

4.4.1 Comparison of Base Scenario and Single Decision Set Scenarios (#1 - #5)

In scenarios 1 - 5, Social Demand Response (SDR) (including $\overset{+}{SD}$, the positive response, and $\overset{-}{SD}$, the negative response) and Initial Operator Skill Levels (including ψ, operation efficiency, and Ψ, decision speed) are held constant. The only difference are the inclusion of a single decision set exclusive to each scenario apart from the base scenario (where no decisions are made).

The base scenario (#1), has a mixed performance compared against the initial scenarios #2-5. All scenarios start with a negative balance ($4,423) as it is assumed that capital costs are borne by the project itself (though at no interest). The base scenario has no decision-making throughout the simulation: no energy price adjustments, no investment in skills, and no adjustment in load availability targets. Little variation in financial performance between the simulations is seen in years 0-5 and no project has yet achieved break-even (zero balance). In years 5-10 the base scenario is grouped with the technical (#2), economic (#3), and organisational (#5) scenarios with the social scenario (#4) performing slightly better. By year 20, the final year included in the simulation, the base model has a balance of $1,522, shown in Figure 4.18 and has managed to outperform all but the organisational scenario. Reliability of the system, using load not served as metric, public (free) and private (paying) was 72 kWh/yr and 105 kWh/year, respectively. Meanwhile, without an ability to make a decision on investing in operator skill levels, the base simulation shows almost no change in operating efficiency over the 20-year simulation, remaining at 80%. In fact, only scenario #5, which has the organisational decision set, has any meaningful improvement of skill levels.

Scenario #2 adds the technical decision set to the simulation. This decision ensures that the target availability of the private load is starts at 90%. The operator will increase this target if utilisation is low. If unmet load in the last period is below this threshold, the operator will reduce the public load availability target to ensure the private load availability target is met. The results of this behaviour is clearly seen in Figure 4.19 where the public load served has the steepest downward trend. It is the worst performer, by a wide margin for public load served (by year 20, only 49.9% of

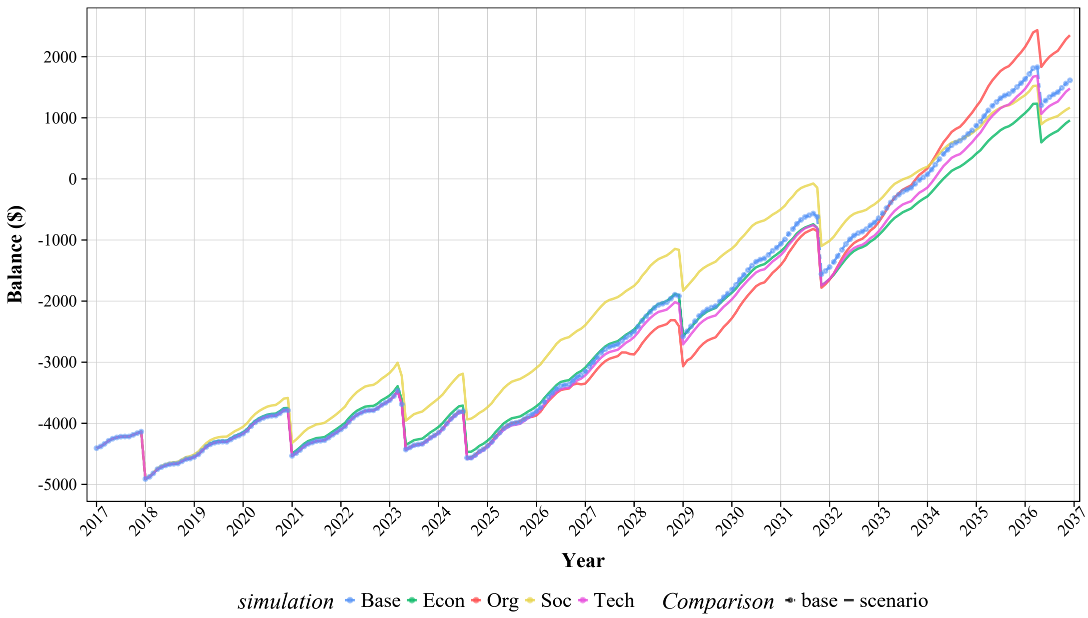

Figure 4.18: Project Finances - Monthly Project Balance

the social scenario #4), and though it has a high reliability for the private load, the overall private load demand depressed due to the SDR effect. The scenario finishes with a final balance of $1,377 and is in the middle of the pack versus the other initial scenarios.

This result demonstrates the trade-off when prioritising a high private load availability, load which is charged for their energy consumption, and how that affects overall demand. Inspection of Figure 4.18 shows in the first 5 years the project balance is similar to the other scenarios. However as load utilisation gets higher due to steady load growth, the technical decisions begin to reduce the target availability of the public load. With the base simulation parameters, the most negative SDR effect supresses overall demand of the private load by 50%. Moreover, there is an opportunity which this scenario misses: achieving the target public load availability could boost the private load demand by 50% – in all this is a potential swing of 100%. In 2037, scenario #2 achieves public availability of ˜22%; compare this to the social scenario of ˜50%, resulting in -28% modifier of private load demand in comparison.

The economic decision set is shown in scenario, #3; this allows the operator to

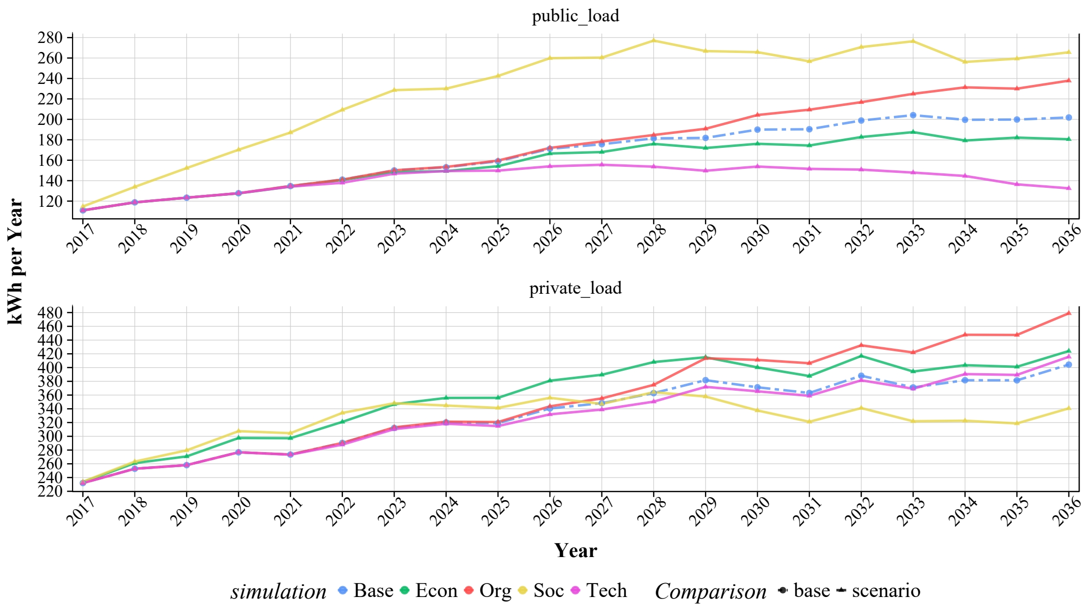

Figure 4.19: Yearly Public and Private Load Served

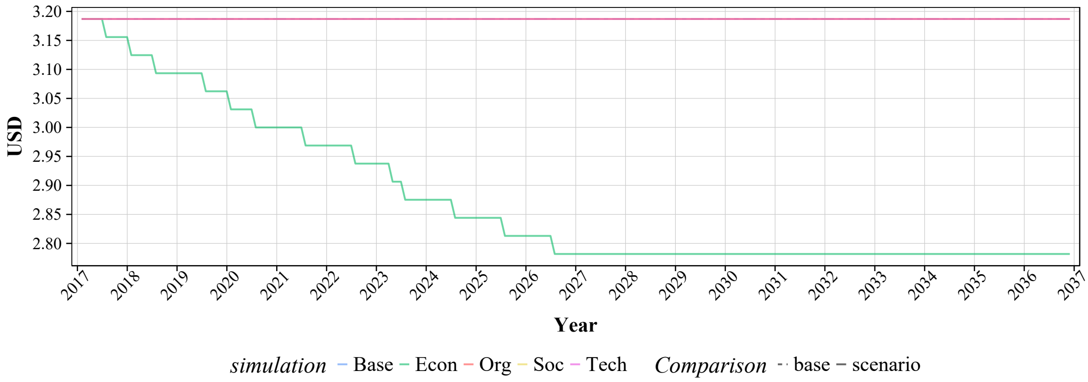

Figure 4.20: Average Energy Price

adjust the price of energy in order to increase or decrease demand with the overall goal of ensuring an adequate level of savings. Within this set of simulations, the scenario #3 is the only one to adjust prices from initial setting (about $3.186/kWh) as shown in figure 4.20. Prices sharply decrease in years 1-10 down to ~$2.75/kWh and stay relatively steady throughout the rest of the simulation. This behaviour is expected as demand is similar to the other scenarios at the start of the simulation, with excess energy being produced. The lowered price increases load demand due to the PED effect. Over time, as load grows, utilisation factor increases and the operator responds by stablising prices. This dynamic is visible in figure 4.19 where private load served is consistently higher than the base scenario and sums to 531 kWh over 20 years. Compared to the technical scenario, the strategy achieves a higher public availability, but lowered private availability and financial performance. Versus all initial scenarios the lowered energy price, especially after load growth takes off in years 10-20, makes the economic scenario perform relatively poorly with a final balance of $908, the worst of the group.

The social decision set is highlighted in scenario #4. This decision set prioritises supply to the public load at the expense of private load availability. Over the course of the simulation, these are adjusted significantly, by year 2036 the private target remains at 90% demanded while the public target is over 100% (starting at 50%) as shown in figure 4.21. Due to the SDR, high levels of public availability result in increased private demand. Thus, while the operator has not adjusted the target private availability, the absolute private demand maintains a consistently higher demand compared to the base scenario #1. Scenario #4 has the highest public load served at 266 kWh in year 2036 compared to 202 kWh for the base scenario and 133 kWh for the technical scenario #2. In fact, the scenario manages to achieve nearly double public load served, against all other scenarios, by year 2023. Financially, the strategy performs very well in years 5 - 15. However, afterwards load growth and its preference to favour the public load allows other scenarios to outperform it and finishes with a second worst balance of $1,173.

The organisational decision set is shown in scenario #5. Overall the result is very similar to the base simulation, tending to outperform it slightly on almost every measure. Financially it is the best performing scenario project balance of $2,164 in year 20. One notable difference is the improvement in operating efficiency as monthly profits are invested in training. By the end of the simulation it achieves a 100% operating efficiency, see Figure 4.22. Slight improvement in operational efficiencies due to learning by doing are made until year 2025 after which a higher income provides an opportunity to make more substantial investments in training. By 2029 the maximum efficiency is reached. The additional 20% energy that can be utilised is modest but does reduce

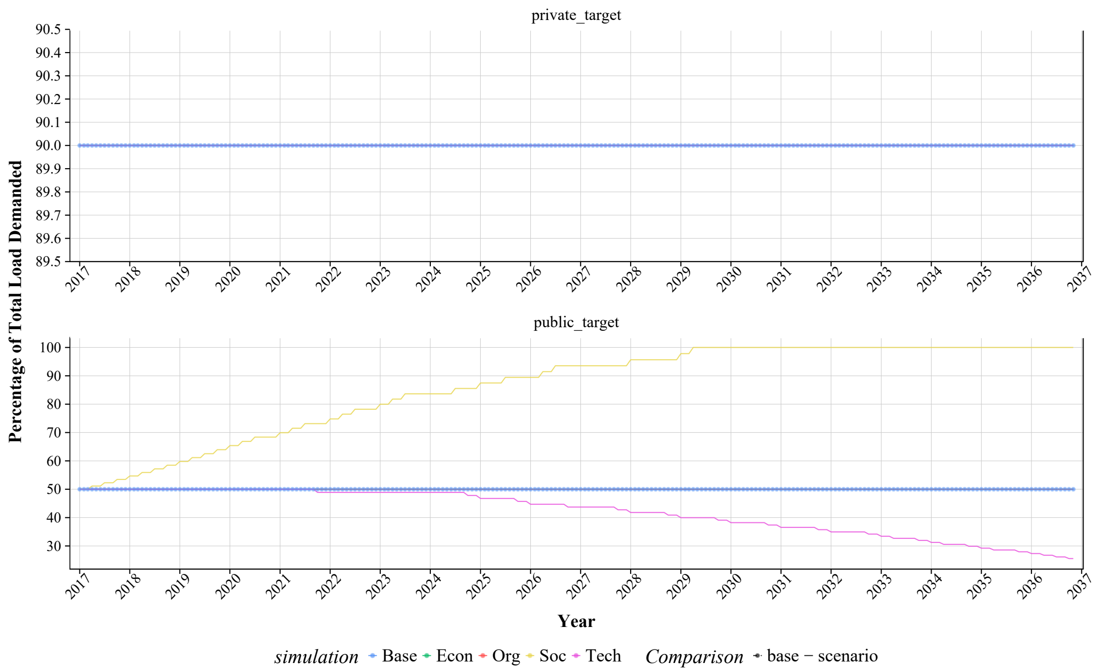

Figure 4.21: Target Availability

public and private energy not served compared to the base scenario by 36.1 and 44.5 kWh, respectively. The scenario has a distinctive financial performance. Over years 10 - 15 of operations, investments in training inhibit its financial performance compared to the other scenarios. However, as operational efficiency improvements increase, income for the organisational scenario is markedly steeper.

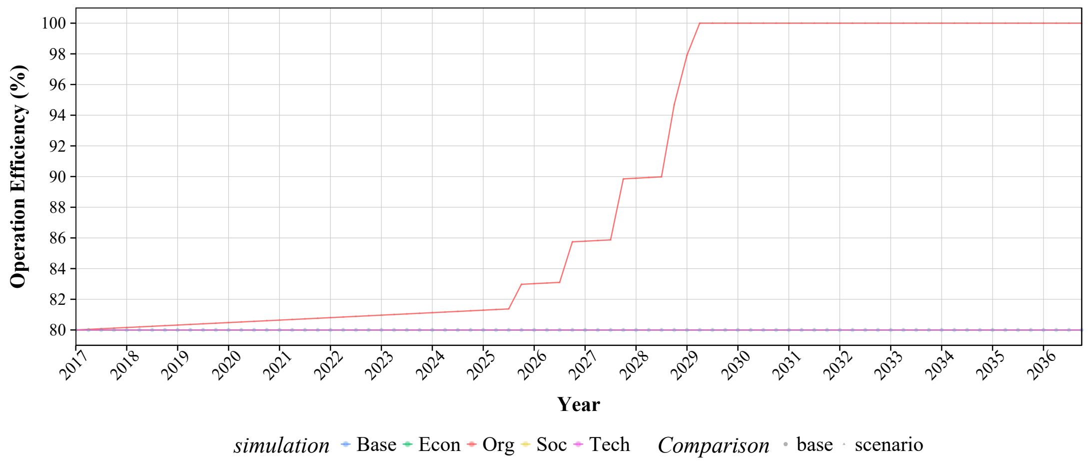

Figure 4.22: Operational Efficiency

Results from the initial scenarios provide some interesting insights. Briefly, they include the impact of added complexities (social demand response, price elasticity of demand, and operator decisions), how to judge the optimal result, the level of validity of results in the project planning phase, *best* strategies over time.

First, it can be observed that incorporation of the complexities not typically considered in a techno-economic optimisation has a significant impact on project performance. This is apparent when considering the social demand response. The relatively strong financial performance of the social decision simulation (#4) during the first years of operation. Figure 4.23 plots the load demand adjustments of the private load due to the SDR affect over the course of the simulation. Although the divergence of social scenario and technical scenario (#2) happens almost immediately, by the end of the simulation the social scenario achieves about 28% greater demand. It was shown in Chapter 3 that social engagement, satisfaction, and acceptance of a project is considered by the literature as a necessary component to sustainability. The result from this analysis support that view and provide an initial means to model the relationship whereas in the reference model, for example, it is entirely omitted.

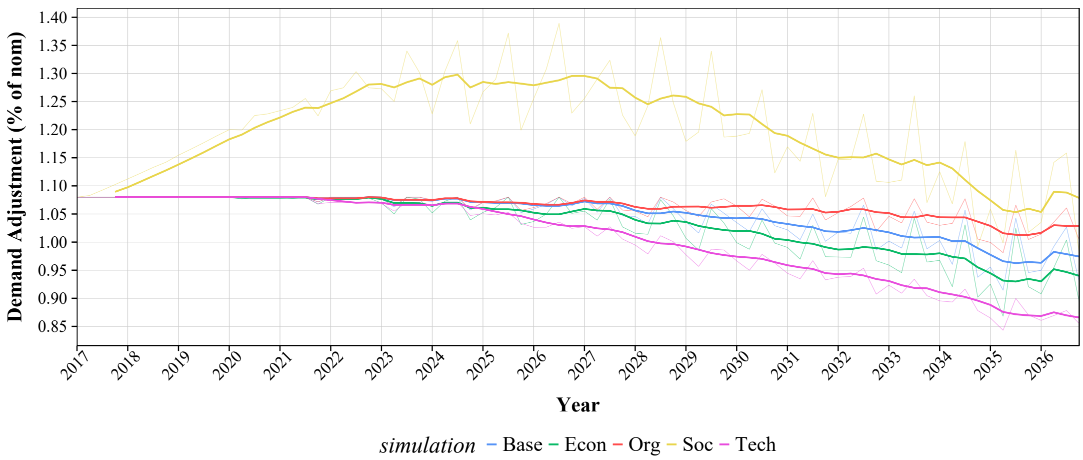

Figure 4.23: SDR Impact on Private Load Demand

Not every project will be subject to a social demand response to this level nor will it be realised in this particular way. However, failure to recognise the mechanism and, in this model, prioritise energy to the public load (health centre) misses a large opportunity to boost demand especially when it is low. Scenario #4 outperforms the base in public load served with a net difference of +1.27 MWh public load served over the course of the 20 years. In many development programmes, an outcome which successfully supplies power to a critical facility, in this scenario a health centre, would be considered preferable as it will directly relate to development outcomes (i.e. improved health). While it has the highest relative private load not served (221 kWh compared to 105 [#1] and 40 [#2]) it is largely due to additional demand brought on by the community supporting the project.

Figure 4.24 plots the proportion of total energy demanded to maximum potential generated. The horizontal red line labelled 'Maximum Supplied' is fixed at 100%, which represents the supplying of all potential energy generation that could be produced (minus technical losses). A point below the line is effectively wasting energy that could be produced and used, while a point above the line is consumption that cannot be served. Wasted energy reduces overall system utilisation and reduces potential revenue. Consumption not served is also a negative outcome as it represents a lost opportunity. Since the generation potential is fixed, strategies that can adjust the demand closer to the 100% level avoid either negative outcome. The initial scenarios are shown to achieve varying utilisation levels throughout the simulation with the social and economic scenario making the most aggressive use of resources and the technical scenario the most conservative. Additionally, though it is not modelled here, it is shown in the figure that system expansion may vary significantly depending on the operator decision-making.

Another complexity is price elasticity of demand, which has an significant effect on the results. The economic decision scenario (#3) was the only that allowed the operator to adjust prices according to demand for energy, shown most clearly in 4.20. The existence of price elasticity means that demand will be reduced if prices increase and vice versa. Awareness of this relationship and subsequent decision-making allowed the operator to boost demand in the early stages of the project and better utilise the available generation. As PED has a powerful effect on overall project performance it is discussed later in the analysis for scenarios (#19-#23).

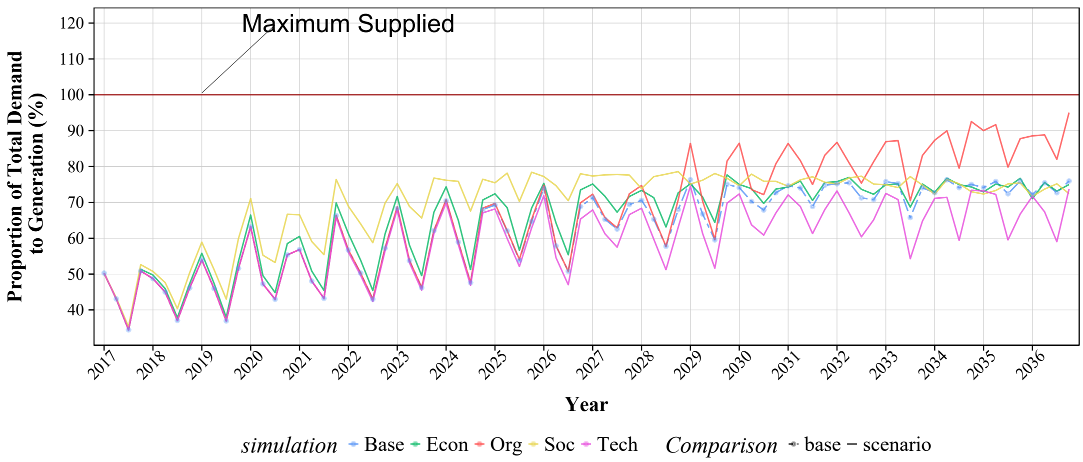

Figure 4.24: Energy Demand Versus Generation

The final complexity, it was clear that the inclusion of operator decisions produced many variations on the overall outcomes. Variance occurred in availability for both the public and private loads, income levels achieved, and operating efficiency. An operator that favours one decision over another may have a difference in final project balance of $1,256 in this case between the organisational scenario (#5) and economic scenario (#3). This result sheds light on the trade-off that often occurs in projects where two optimising criteria may exist but only one achieved at the expense of the other. Pursuing high availability for the public load (as per #4), one optimal point, meant the overall demand was not as well managed (as per the technical scenario #2). Equally, it can be shown that dependency on a single decision set can sometimes have a negative outcome: the social scenario in the end stimulated too much demand and had reliability issues, the organisational scenario in years 10-15 was the worst financial performer, and the technical scenario consistently had the lowest utilisation. A major area of interest is the combination of decision sets and prioritisation of decisions which is conducted in scenarios (#6 - #10).

It was shown previously that different designers and toolkits provide greater emphasis on different sustainability factors or are neutral. At the project design stage when modelling is conducted, it is feasible that any one decision included thus far could be established. One organisation, for example, might emphasise private availability and another public availability for the same project parameters. Thus, all outcomes of the initial scenarios could be equally considered valid depending on the preferences of the design organisation. With such variation in outcome, even in this structured simulation (relative to the real-world), the results suggest that designers must address the complexity and potential scenarios which could affect any one project at the planning stage. Design stage planning around mechanisms which affect electricity demand, such as the PED and SDR effects expressly modelled here, must also characterise the decision space during operations.

A last insight from the initial scenarios is that the preferable strategy, based on the decision set used, changed throughout the simulation. The social scenario (#4) aggressively targeted high public load availability and in doing so, boosting private load demand through the SDR effect. However, in the last 5 years, the singular preference of public load availability ultimately led to reduced yearly income as private load demand dropped. Meanwhile, the organisational scenario (#5) invested profits into training over years 10 - 15 leaving it susceptible to short-term financial shocks such as occurs in 2029. Although negative project balances are assumed to be possible through no-interest finance, a financial stricter requirement would leave this project the most exposed to default. Despite this, after year 15, more efficient operations in this scenario increase overall utilisation and substantially improve financial performance in the years following. In short, since the 'best' operation strategies may indeed adjust throughout the project life-cycle, an ability to adapt by adjusting decision preferences would allow a project to maintain higher sustainability.

4.4.2 Evaluation of Simulation Sensitivity to Social Demand Response (#11 - #14)

It was shown earlier that social decision scenario (#4) was able to exploit the SDR mechanic positively. Since it clearly had the potential for a strong impact, it is important to further evaluate the overall impact on the simulation outcome. In this section, scenarios #11 through #14 test various combinations of SDR using only the social decision set. The results can be compared against the scenario #3 which is has the SDR

range of $[0.66, 1.5]$ used in all other scenarios. All SDR scenarios use the base operator skill level assumptions. Recall that social decision set seeks to maximise social load availability by reducing private availability target (freeing up capacity to serve public load) or increasing public load target, to a maximum of 100%. This choice depends on whether the current utilisation is high (reduces private availability target) or low (increasing public availability target).

Scenario #11 assumes there is no negative ($\overset{-}{SD}$) or positive ($\overset{+}{SD}$) impact associated with low or high service availability to the public consumer. The social dynamics of each project differ so it is entirely possible that no SDR effect manifests in a given project. For the reference simulation, the base assumption is no SDR effect. In Figure 4.25 the yearly public and private consumption illustrates that scenario #11 has a higher public load compared to the base scenario (#1) - around ~280 kWh/year at year 20 versus 200 kWh/year. On the other hand, private load served is significantly lower than the base scenario, a difference of ~340 kWh/year; since there is no SDR in the scenario the operator behaviour to increase public availability has no impact on the private load demand. Scenario (#13), where ($\overset{-}{SD}$), penalty, is set to 0.5, has a lower private load served but the highest public load served. This is explained by the low public availability reducing general private load demand which frees up capacity for the public load. Compared to the other scenarios, (#13) is the most under-utilised due to this relationship. Conversely, the high ($\overset{+}{SD}$), reward, scenario (#12) achieves the highest private load, a difference of 140kWh/year compared to #13 despite having the lowest public load availability of all scenarios.

The level of SDR effect over time is shown in Figure 4.26. This adjusts the demand for the private load. As expected, the scenario #11 shows no variation, meaning private load consumers are indifferent to the public load availability. In remaining scenarios the demand adjustment is held fairly steady as the operator responds to load growth and seasonal generation shortages by either diverting power from the private load or increasing the public target availability. Simple moving averages, the thick solid curves, show that over time load growth tends to decrease availability and, due to SDR, results in lowered demand. The one exception is where there is no SDR effect, scenario #11.

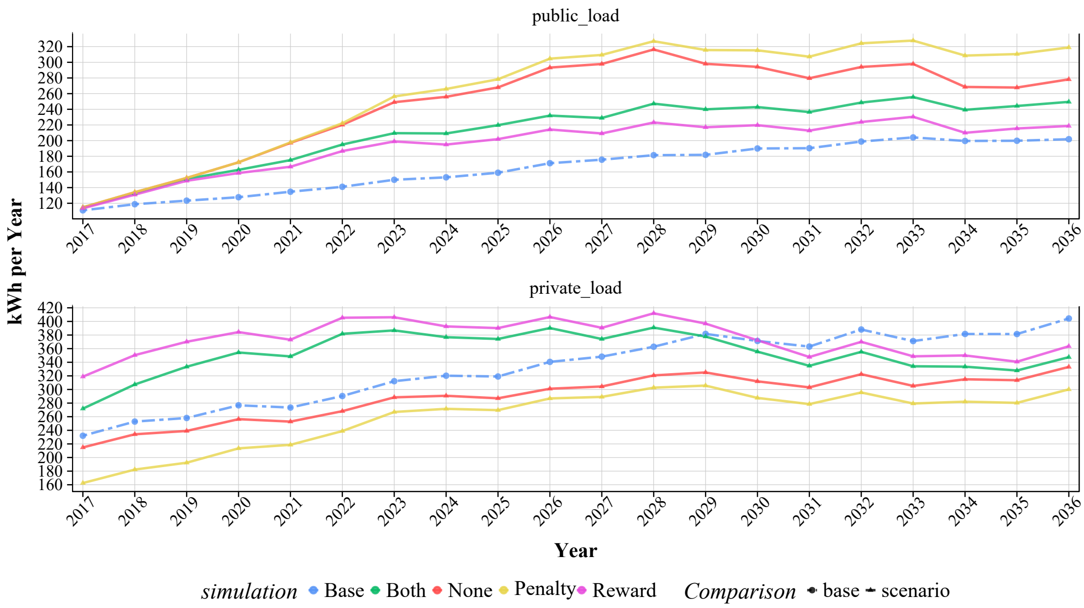

Figure 4.25: Yearly Public and Private Load Served - Social Demand Response Scenarios

Figure 4.26: Demand adjustment due to SDR effect

All scenarios #11 – #14 include the social decisions which increases availability to the public load, whereas the base scenario has no decision-making. Adjustments to the targets for both loads are shown in Figure 4.27. As expected the base scenario makes no adjustments and remains at the initial set points. A pattern emerges for the other scenarios on handling availability targets: while demand is low, the public target is increased. The timing corresponds to the utilisation levels - those scenarios with higher ($\bar{SD}$) effects (notably the penalty scenario #13) have lower utilisation and thus act more rapidly to increase public availability targets compared to scenarios with lower ($\bar{SD}$) effects (for example, the reward scenario #12). At the end of the simulation, scenario #13 (penalty achieves the highest public (∼60%) and second highest private (∼65%) availability while scenario #12 (reward) has the second lowest (∼40%) public and lowest ∼45% private availability.

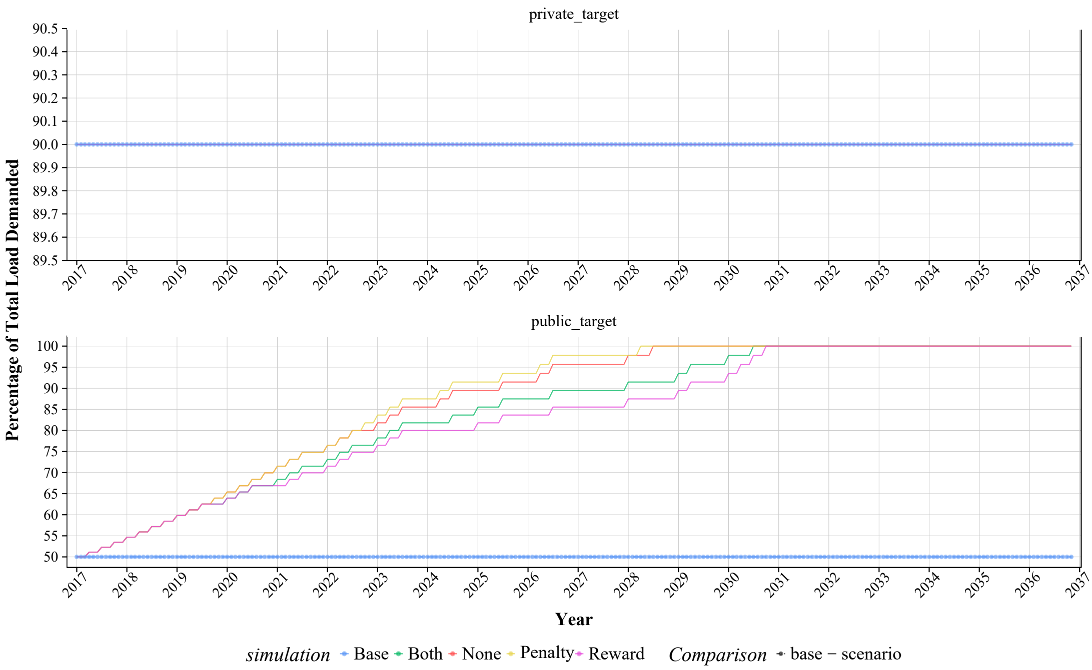

Figure 4.27: Target Availability for Public and Private Loads - Social Demand Response Scenarios

For project finances, a community which has a strong reward mechanism can make an immediate and significant financial impact as show in Figure 4.28. The pink curve, representing the reward scenario #12 ends with a positive balance of \$7,810, the highest of all 29 scenarios. The penalty scenario #13 meanwhile ends at (-\$830) despite providing for relatively high public energy use. The base scenario ends with \$1,522 despite no decision-making mechanism – the parameters are there for moderate and suitable for the general simulation.

The results of the SDR scenarios demonstrate the importance of local demand effects

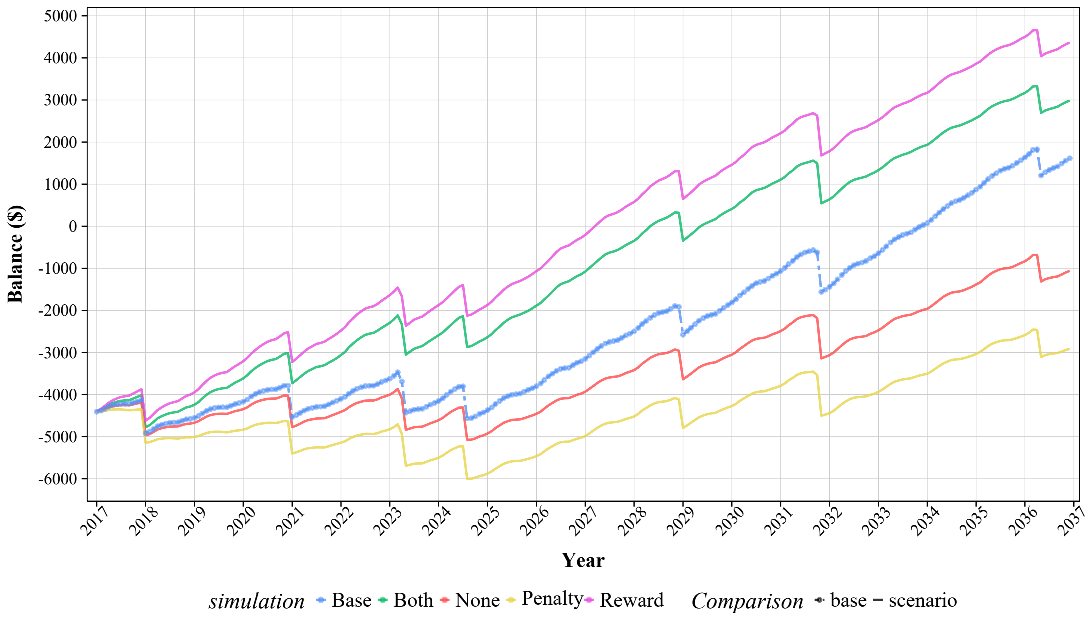

Figure 4.28: Project Finances - End of Year Balance- SDR Scenarios

on the sustainability outcome of the project. Projects with more reward potential were able to attract significantly more private demand while performing poorly in terms of reliability when compared to situations with more penalty effects.

4.4.3 Organisational Skill Level Scenarios (#15 – #18)

In scenarios #15 – #18 the initial operator skill level is varied in and impact on project performance calculated. Recall the base conditions for operator skill was characterised by operational efficiency $\psi = 0.8$, and decision speed, $\Psi = 3$. Operational efficiency ranges between $[0, 1]$ and modifies the maximum generation potential of the panels (after other losses are considered). Operational efficiency used here includes all non-technical aspects (not already considered) of the business operations. The literature review identified many aspects which could fit in this parameter: poor marketing/sales routines, poor customer management, lack of understanding of charging cycle/poor charging management, lack of spare parts delaying replacement, hours of operation not maximising potential customers, etc. While these aspects are recognised in the literature, there has been no formal efforts to model these relationships. Hence, though the approach here is relatively simple, it provides a useful starting point to validate the literature and a basis for more detailed modelling.

Similarly, decision speed, used here, is motivated by the need for sufficient time to make informed decisions in an environment where skill levels are typically low, availability of data for decision support is limited, and tools to conduct analyses (computers) are not available. It within reason that it may take a month or several months to make a decision modelled in this simulation, for example a pricing change. Additionally, the abstracted case in this simulation is that a single person, the operator, makes decisions; in practice a deliberative approach with various stakeholders may occur. Lack of formal background was common in the MREAP PV Sustainability study and many roles for projects were filled by school staff or health officers [202]. A higher decision speed parameter, Ψ, implemented here, corresponds to a more regular application of the decision set(/s) that the operator knows. It is also useful for handling seasonal trends and responding quickly to long-term changes (i.e. load growth).

The organisational decision set allows the operator to invest in training which then increases operational efficiency and decision speed. In the 'high skill' scenario (#15), initial operational efficiency is set to 0.95 and a decision occurs once every month. As a result of the high initial skill levels, the project benefits from increased energy generation and quickly makes investments to achieve maximum efficiency. Investments for the high skill scenarios occur on year 5, once sufficient profits are made and are enough to achieve maximum efficiency, shown in Figures 4.29 and 4.30. The other scenarios #16 - #18, with lower initial starting skill levels, continue training investments over longer periods. For the 'medium skill' scenario, #16 ($\psi = 0.9$), this occurs over years 7 - 9, for the 'low skill' scenario ($\psi = 0.85$), over years 9 - 13. Finally the 'very low skill' scenario ($\psi = 0.7$) fails to make any profits and as such unable to make any training investments. This is interesting as it implies that failure to have sufficient initial starting skill levels can act as a type of lowered equilibrium where the starting point for the positive feedback loop is never reached.

Skill investment translates into higher operational efficiency which increases the total energy available for consumption. In Figure 4.31, which shows the total load

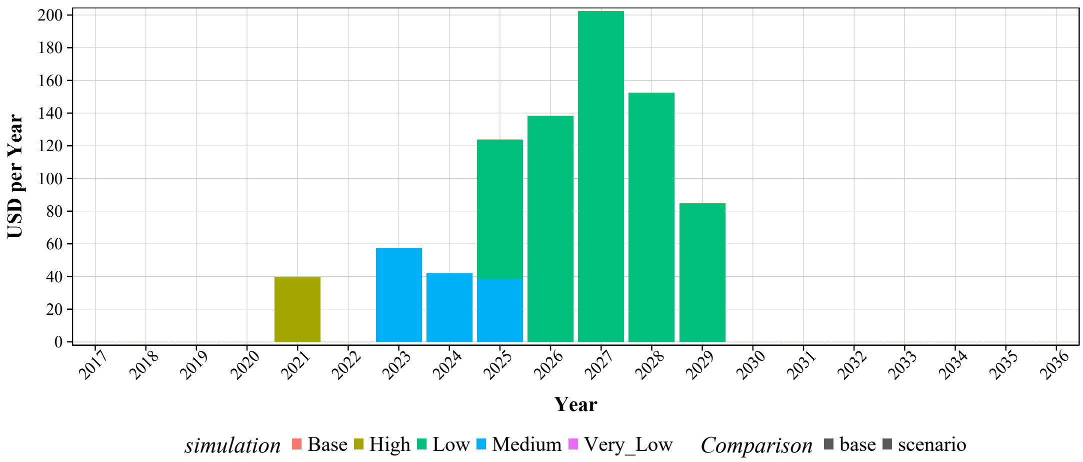

Figure 4.29: Training Investment per Year - Operator Skills Scenarios

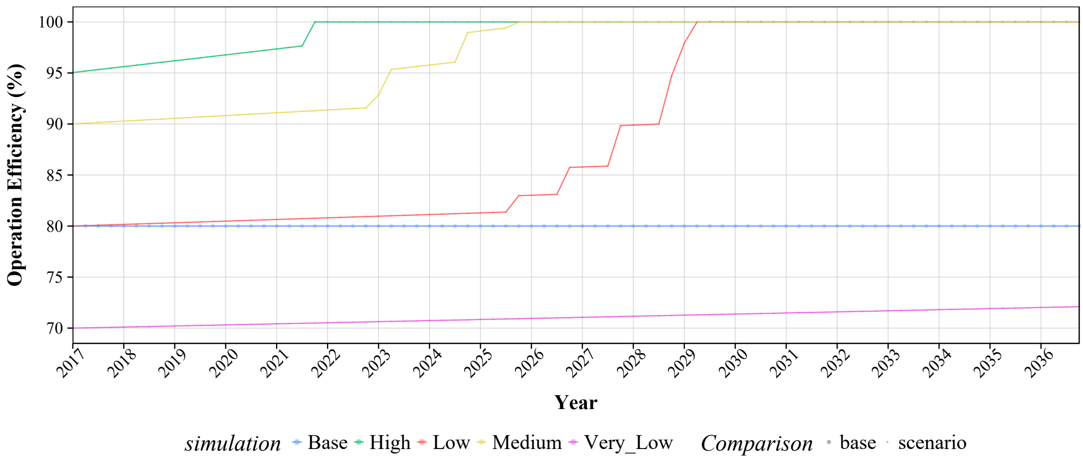

Figure 4.30: Operation Efficiency - Operator Skills Scenarios

served per year, a gap in the public and private corresponds to the training periods. A battery energy profile, shown in 4.32, shows the typical cycling pattern for each scenario over course of the simulation. By 2026, the high and medium skill scenarios maintain a minimum state of charge of ~85% whilst the low skill and base scenarios are ~80% and very low skill is ~75%. By the end of the simulation, after load growth as accumulated, the charging cycles of all scenarios have shifted downwards and have significantly worsened. However, as a result of high operational efficiency, scenarios #15 - #16 typically avoid the charge controller cutoff level at 50% and have a maximum daily charge at ~75% of capacity, around 10% higher than the base scenario and 15%

than the very low skill scenario.

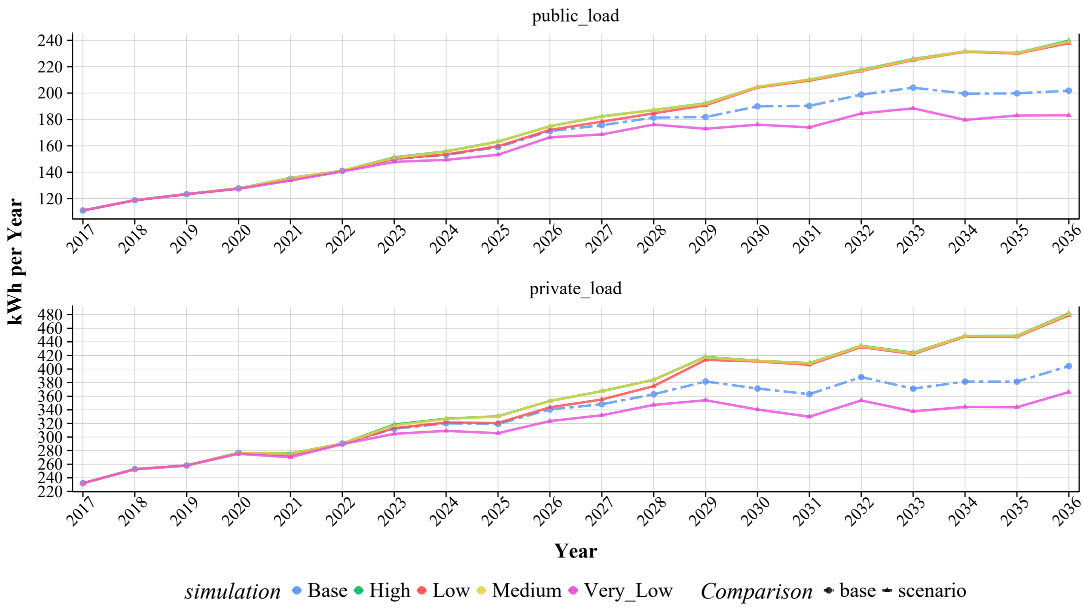

Figure 4.31: Total Load Served Per Year - Operator Skills Scenarios

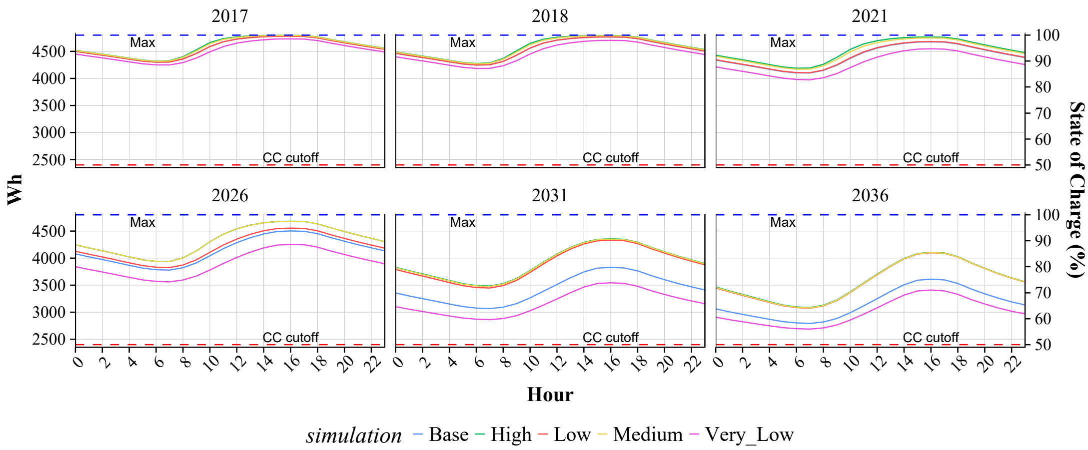

Figure 4.32: Daily Battery Energy Profile - Operator Skills Scenarios

As expected, higher operational efficiency, earlier in the simulation, corresponds with higher project balances as shown in Figure 4.33. However, the investments with the added financial burden leave the projects more susceptible to financial issues particularly in the middle term of the simulation. All scenarios, except the very low skill scenario, significantly outperform the base scenario: the high skill scenario ends with a balance of \$3,008. The very low skill scenario despite higher incomes in later years, trails behind the base scenario balance as the gap opens up around year 8; it ends the simulation with \$1,091 less. The low skill level scenario has an interesting profile. Over years 10 - 16, due to investments in training, it has around \$350 less than the base scenario until it eventually raises its income. This raises the question whether the investment, at such low initial levels, was worthwhile given a total of \$663 was invested over the simulation. It can be noted that the result may also be from model effects due to the skill growth model used herein, namely a linear relationship between investment and improvement. A reasonable conjecture may assume higher marginal returns on investment at lower skill levels, though this not tested here due to limitations in available evidence pointing one way or another. Conversely, operator turnover may have an adverse effect on operations efficiency.

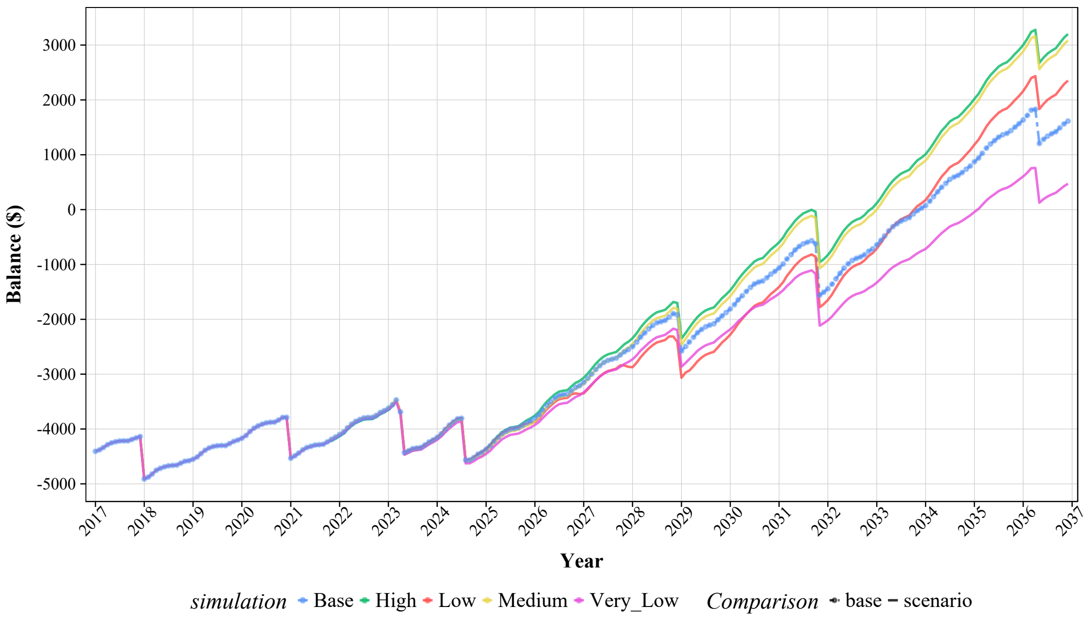

Figure 4.33: Project Balance - Operator Skills Scenarios

The skill level scenarios demonstrated how non-technical, operational level inefficiencies impact the project performance. Higher skilled operators converted higher proportions of the energy available to the project into additional load served and achieve higher incomes after paying back the costs of the training investments. Generally, this supported and justified the organisational decisions made, even though there was added financial burdens for the lower skill scenarios.

4.4.4 Price Elasticity of Demand Scenarios (#19 – #23)

Price elasticity of demand (PED) is varied throughout scenarios using the economic decision set. Recall that PED is an inverse relationship of price and demand for a given product, in this case electricity demand. A PED of between 0 and -1.0 refers to an 'inelastic' good, when price increases by 1%, demand decreases by less than 1%. Conversely, a PED less than -1.0 is an 'elastic' good; when price is increased by 1%, demand decreases by *more* than 1%. As the simulation is designed to allow for operators to adjust the pricing periodically, it is important that a reasonable demand adjustment occurs accordingly. The scenarios vary from a highly elastic PED of -2.0 to very low elasticity PED of -0.25. Recall that literature review found a PED of around -0.66 to -0.75 though field data in Malawi suggested a PED of -1.195. The scenarios are compared against the base scenario #1, which uses a PED of -1.5, which assumes a slightly more elastic market as new consumers are more responsive to price changes.

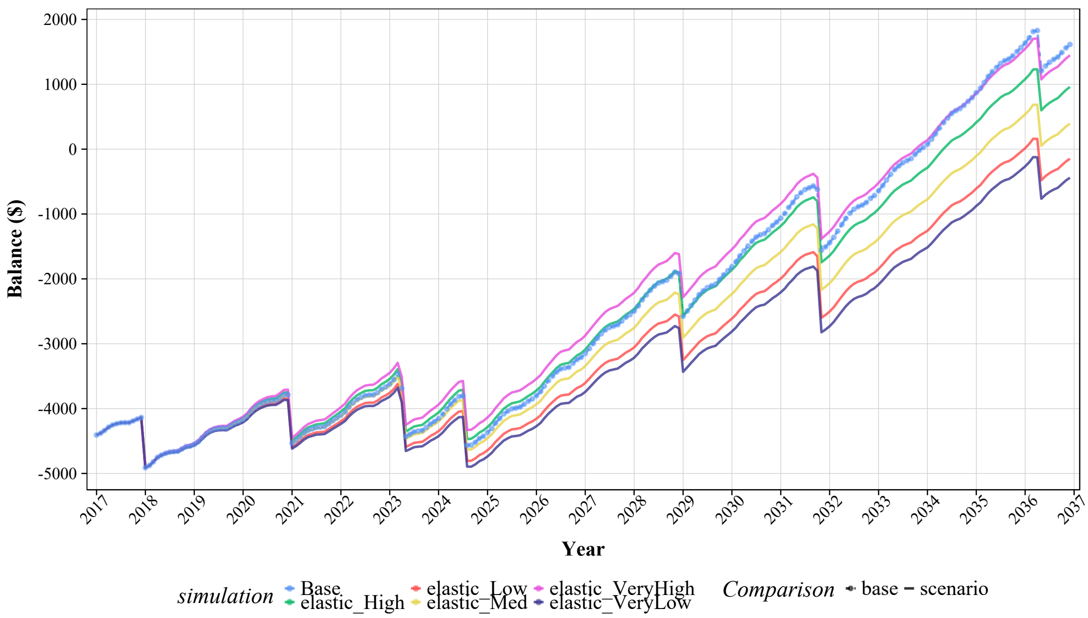

Figure 4.34: Project Balance - PED Scenarios

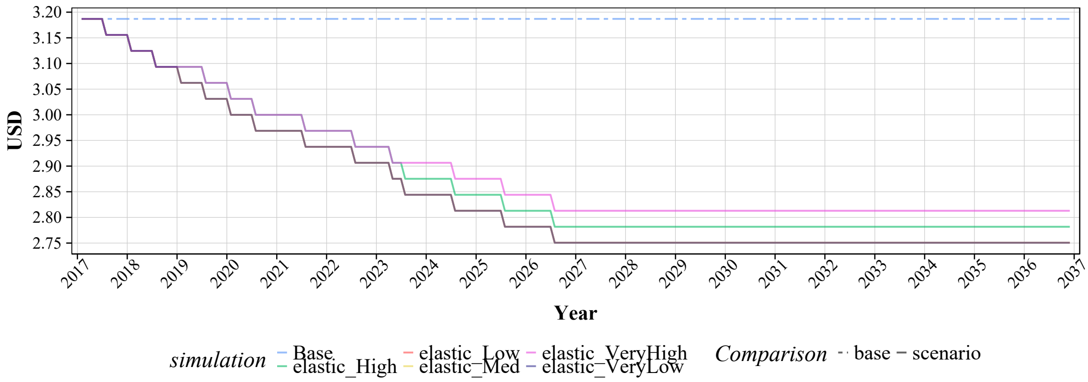

Figure 4.35: Price for Electricity - PED Scenarios

In Figure 4.34, project financial balances are plotted for each PED scenario and compared against the base scenario. All but the base scenario use the economic decision-making, or in other words, decrease the price in order to increase demand or vice versa. Figure 4.35 show that in each scenario, prices are gradually reduced for the first 10 years and hit a low point at $2.75 to $2.85. For the medium, low, and very low elasticity scenarios (#21 - #23), the price curves are identical as each try to drop prices as quickly as possible until a higher utilisation is achieved. This behaviour follows the general trend seen in other scenarios to increase demand in the first years before load growth accumulates. Financially, over the first 10 years the high elasticity scenario (#20) achieves a slightly higher balance compared to the base scenario. Additionally, the very high elasticity scenario (#19) has a higher balance for the first 16 years, all the other scenarios do poorer financially with the more inelastic the PED.

The impact of the price reductions is shown in Figure 4.36 for the PED scenarios. Clearly private demand increases more with the higher elasticity scenarios, reaching an additional 24% for scenario #19. For scenario #23, the most inelastic scenario, demand is only 3.8% despite price decreases nearly as aggressive as the other scenarios. As can be seen from the Figure 4.37, the increased private load reduces the public load availability that produces countering effect. This affects higher elasticity scenarios (i.e. #18) more heavily (roughly 5% less demand) than low elasticity scenarios (#23).

The consumer response is interesting in that they do indeed demand more electricity when prices decrease but abated by the community simultaneously penalising the

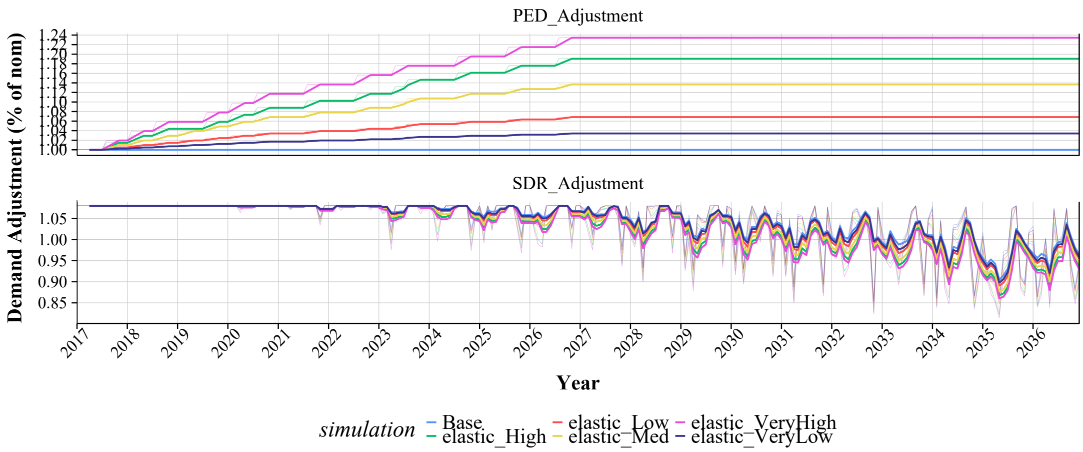

Figure 4.36: Demand Adjustments - PED Scenarios

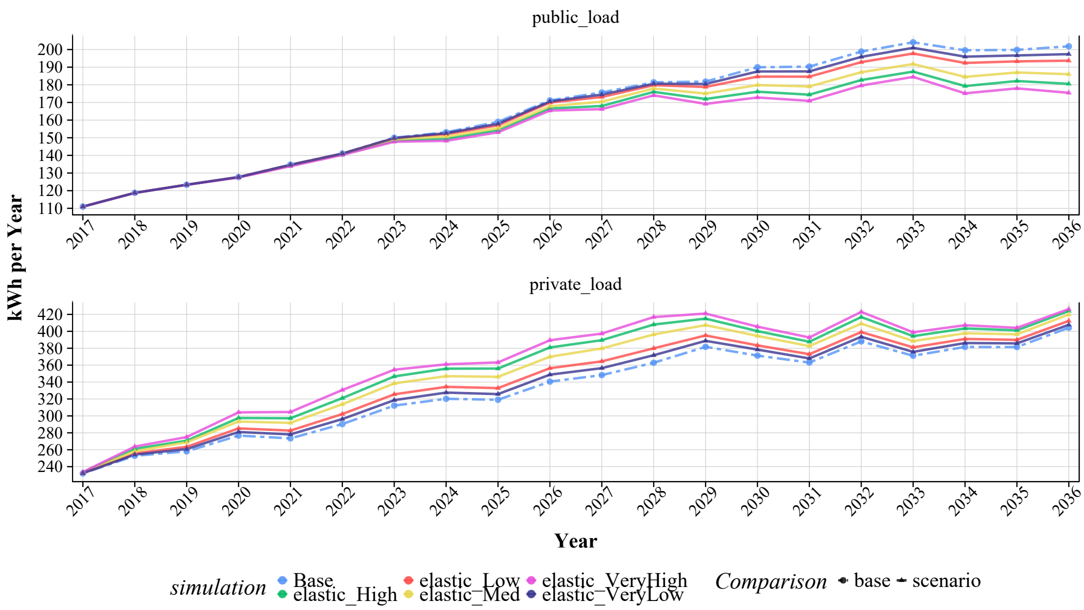

Figure 4.37: Load Demand Public vs. Private - PED Scenarios

operator (through SDR) when they fail to provide public availability. The implications shown here for the operator are that exploiting the PED effect through lowered prices is viable when demand is low and elasticity is high and when there is little reason to expect a strong penalty from the community. In a low demand, low elasticity environment, decreasing the price is not supported as the net effect was lowered income. Although not shown in the PED scenarios, a situation where demand is high and elasticity is low, the option to raise prices (and reduce load demand) should be viable. This is explored more in scenarios with multiple decision sets #6 - #10.

The reference simulation does not allow for any price adjustment to impact load demand. PED was shown in this section to have a significant effect on the financial and reliability outcome of the scenarios suggesting that inclusion of PED in project design modelling is necessary. The highly elastic scenario (#18) significantly raised private load demand and achieved a higher balance than the base scenario in initial years. For markets gaining access to electricity for the first time, willingness to pay is generally lower than established markets that depend on electricity. This result is supported by practical experience where new customers may be willing to switch to electricity (from say candles, paraffin, dry cell batteries) when the price is competitive but will equally switch back if prices are higher than substitute goods.

Discussion around sensitivity parameters

In the previous sections, several sets of 'sensitivity' scenarios were run to explore impact of important initial parameters on the simulation results. Before proceeding to scenarios involving multiple decisions, it is useful to summarise initial results, listed below:

Social Demand Response Scenarios

1. SDR had a strong impact on private load demand: the reward scenario had ∼100 kWh/year more private load than the base scenario.
2. Projects with exceptionally low ($\overset{-}{SD}$) (the penalty scenario) effect had served the highest proportion of public load. Despite this they had the lowest private load as the community penalised the project for not meeting expectations.
3. Projects with high ($\overset{+}{SD}$) (the reward/both scenarios) effect had served a relatively low proportion of public load. Despite this they had the highest private load as the community rewarded the project. Here, the initially low expectations were exceeded as the projects prioritised the public load availability.
4. With no SDR, prioritising the public load simply reduced the availability to the private load, thereby reducing income.

Skill Level Scenarios

1. Higher initial skill level and higher operational efficiency has an immediate impact stemming from the larger proportion of energy generated that can be sold to customers.
2. Investment towards improving the operational efficiency (i.e. training) of the project came at a cost to the medium term sustainability when income is reduced due to the investment itself. With sufficient time, a higher income is achieved so the investment is generally economically rational. In cases where the initial skill level is low, scenario (#17), investments may be less advisable as the payback may take years.
3. Very low initial skill levels may be so inefficient and unable to make a sufficient profit to invest in training. In one case, scenario (#18), the project remained at a low efficiency state that performed poor on nearly every measure considered.

Price Elasticity of Demand Scenarios

1. In situations where demand is low and elasticity is high, the strategy of lowering prices to stimulate demand is viable. In one scenario considered (#19), private demand due to PED was increased by around 24% and it outperformed in the base scenario financially until load demand growth accumulated.
2. Where SDR is present, increased demand due to a lowered electricity price has a counter-effect when it impacts public load availability.
3. Low elasticity scenarios were not justified in reducing prices as the net effect of added customers paying a reduced price was negative.

4.4.5 Scenarios with Multiple Decision Sets (#6 – #10)

This Section considers more advanced scenarios that each include all four decision sets and then evaluated for their sustainability. The parameters of operational efficiency, ($\psi = 0.8$), decision speed ($\Psi = 3$), penalty ($\bar{SD} = 0.66$), reward ($\bar{SD} = 1.5$), and PED (-1.5) are all set to similar levels as per initial single decision set scenarios. Scenarios are named according to their decision priority, for example, "Tech, Org, Soc, Econ" implies that the technical decision set is first priority, followed by organisational, social, and finally economic. For ease, when referring to the scenarios, the labeling employed uses only the first character of the decision. The preceding example is labelled as 'TOSE'.

The decision priority determines the level of adjustment whenever decisions are made as discussed within Section 4.2.6. At each decision set, a first priority decision, if it satisfies the decision conditions and hence is taken by the operator, will make a 6% adjustment (i.e. price or target availability set points). Since decisions happen at regular increments, over time the result of these decisions accumulate into larger impacts, but it also the operator to change their approach when appropriate. Second priority decisions make a 4.75% adjustment, third priority 3.5% and last priority 2.25%. This structure allows higher priority decision to eventually dominate lower priority decisions when there are competing objectives.

The selection of decision order is based on the ranking of initial scenarios (#1 – #5) total yearly load served (shown in Table 4.15, all scenarios shown for reference). Using this measure the most successful scenario with single decisions was with the organisational decision set (#5) followed, by social (#4), economic (#3), and technical (#4); this prioritisation forms the OSET scenario (#6). Other arrangements are considered to determine the impact of prioritising decisions differently. For scenarios (#7 - #9) the first priority organisational decision is replaced by one of the other decision sets. Scenario (#10) is also considered as it is the reverse order of OSET. This selection of scenarios, although not exhaustive, is sufficient to explore the scope of this analysis.

Introducing multiple decision sets produces some unique outcomes not yet seen in previous scenarios. In terms of load served, shown in Figure 4.38, SOET (#7), which prioritises public energy, this is extremely successful in this objective, supplying 480 kWh at year 20 compared to 308 kWh for OSET (#6) and more than doubling the supply in the other remaining scenarios. Conversely, it manages to serve only 168 kWh of private energy, less than half of all the other scenarios and far below TESO (#10) which prioritises private load. EOST (#8), TOSE (#9), and TESO (#10) all have similar patterns to energy served; public energy served is relatively low and ranges between 105.9 to 156.5 kWh. Private energy served is relatively high and ranges between 445.1 and 494.0 kWh. Scenarios begin to diverge in private energy served

Table 4.15: Total Yearly Load Served, Total kWh, on year (1,5,10,15,20)

simulation	No	2017	2021	2026	2031	2036
Base	1	343.7	408.2	511.7	553.4	606.1
Tech	2	343.7	407.4	486.0	510.5	548.2
Econ	3	345.0	431.4	547.5	562.1	604.6
Soc	4	349.4	491.7	615.9	577.9	606.4
Org	5	343.7	408.4	515.7	615.7	716.9
OSET	6	357.3	553.8	654.3	623.4	643.0
SOET	7	360.6	566.8	666.5	622.8	648.5
EOST	8	353.9	528.6	649.7	605.1	616.7
TOSE	9	354.0	520.6	597.1	596.9	601.6
TESO	10	354.0	520.3	591.2	566.6	600.0
No SDR	11	330.3	449.9	594.4	582.7	611.4
High Reward	12	433.4	539.8	620.7	560.5	582.2
High Penalty	13	277.9	416.4	591.5	585.7	619.1
Reward & Penalty	14	387.5	523.7	622.2	571.3	597.0
High Skill	15	343.7	411.4	527.9	618.9	721.4
Medium Skill	16	343.7	411.0	527.9	618.5	719.7
Low Skill	17	343.7	408.4	515.7	615.7	716.9
Very Low Skill	18	343.7	403.9	489.9	503.8	549.3
Very High PED	19	345.4	438.5	554.8	563.7	601.8
High PED	20	345.0	431.4	547.5	562.1	604.6
Med PED	21	344.6	426.0	537.8	561.6	606.0
Low PED	22	344.2	417.2	526.3	557.6	606.1
Very Low PED	23	344.0	412.8	519.3	555.5	605.1

around year 10 as utilisation reaches around 85 - 90% and the social decision set starts scaling back the private availability target (see Figure 4.45). As will be shown later, the SOET scenario aggressively reduces the private load target and increases prices to support public energy demand despite a worsening financial position.

For the financial results, shown in Figure 4.39, all the considered scenarios perform better than the base scenario, which finished with a balance of $1,522, except for

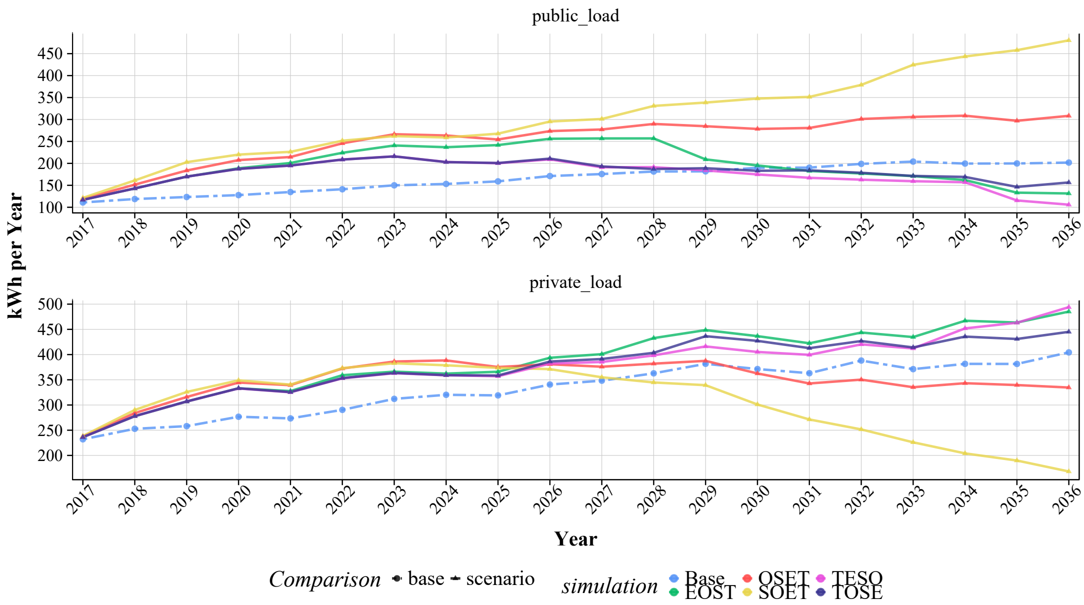

Figure 4.38: Load Demand Public vs. Private - Multiple Scenarios

SOET (#7) which ended with -$179. Like with the private energy served discussed previously, around year 10 this scenario diverges from the other scenarios. The best financial outcome was from the EOST (#8) scenario which finished with a final balance of $3,620. EOST was particularly successful at stimulating private energy demand through a combination of pricing, high private target and low public target.

Pricing (see Figure 4.40 was a key to the strong financial performance of the EOST and TESO scenarios. All other scenarios had the economic decision-making at third or fourth priority. This meant that EOST and TESO could respond more aggressively to the relevant indicator, utilisation, than other scenarios. In response to load growth accumulation, over years 10 - 12, the operator increases prices from $3.05 to $3.20 (per kWh) and reducing the public availability target from ∼85% to ∼55% over the same period (see Figure 4.41). Additionally, as utilisation in consistently reached >∼90% private target availability increased to 100% in year 11.

Study of the pricing approach and target availability helps to explain how earlier it was shown that the SOET scenario dramatically went off track financially at year 12 and finished as the worst performer of the group. The SOET operator, facing high

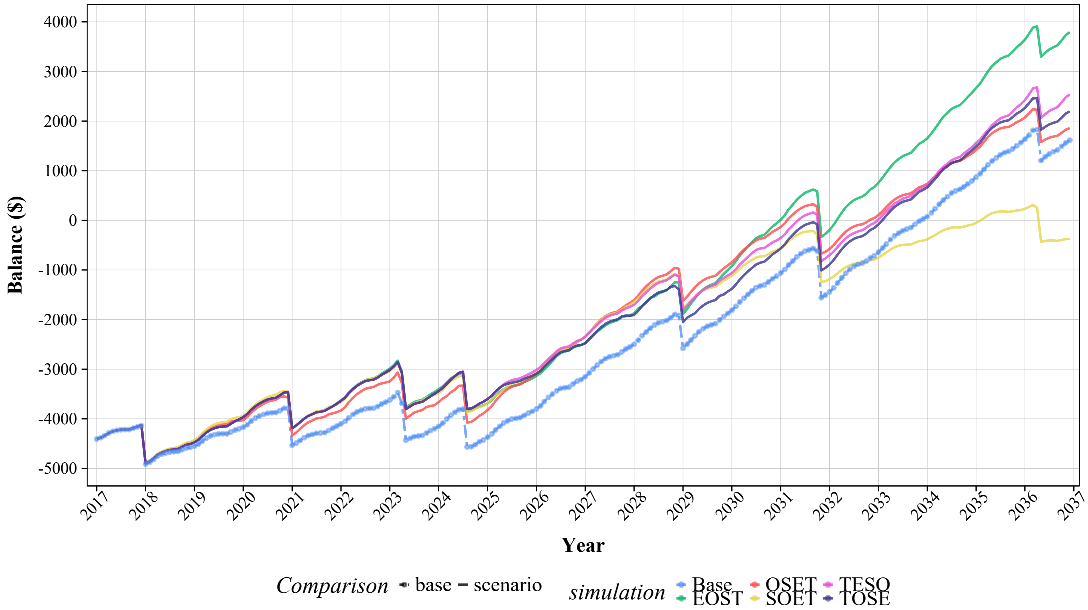

Figure 4.39: End of Year Balance - Multiple Scenarios

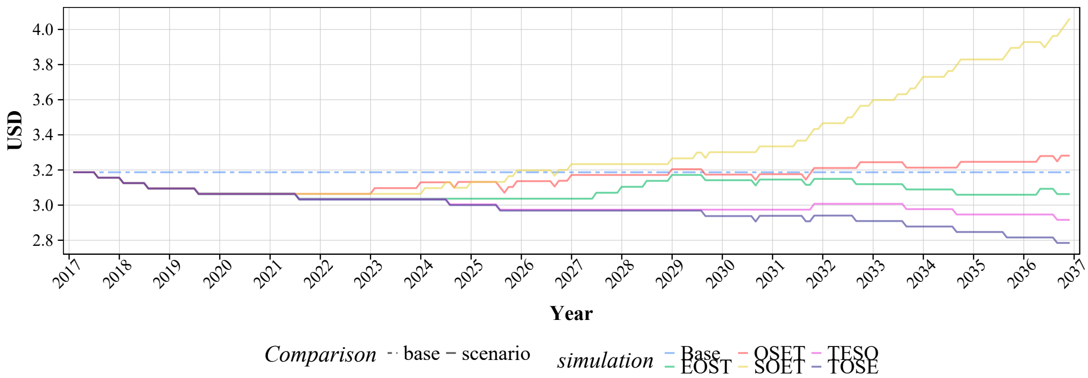

Figure 4.40: Price of Electricity - Multiple Scenarios

utilisation prioritised public energy availability by reducing the private target from 90% in year 9 by roughly 6% per year until it reached a low of 30% in year 20. Second, the price of energy is increased from \$3.20 (starting price) in year 10 to \$3.50 in year 15 and finally to \$4.10 in year 20. This allows SOET to supply the highest amount of power to the health clinic of the scenarios and reduces the private load demand directly through a reduced target and a higher price. However, due to the community rewarding the operator due to SDR (+ ∼35%), demand reduction due to a high price (ranging from

0% in year 10 to -35% in year 20) is entirely off-set.

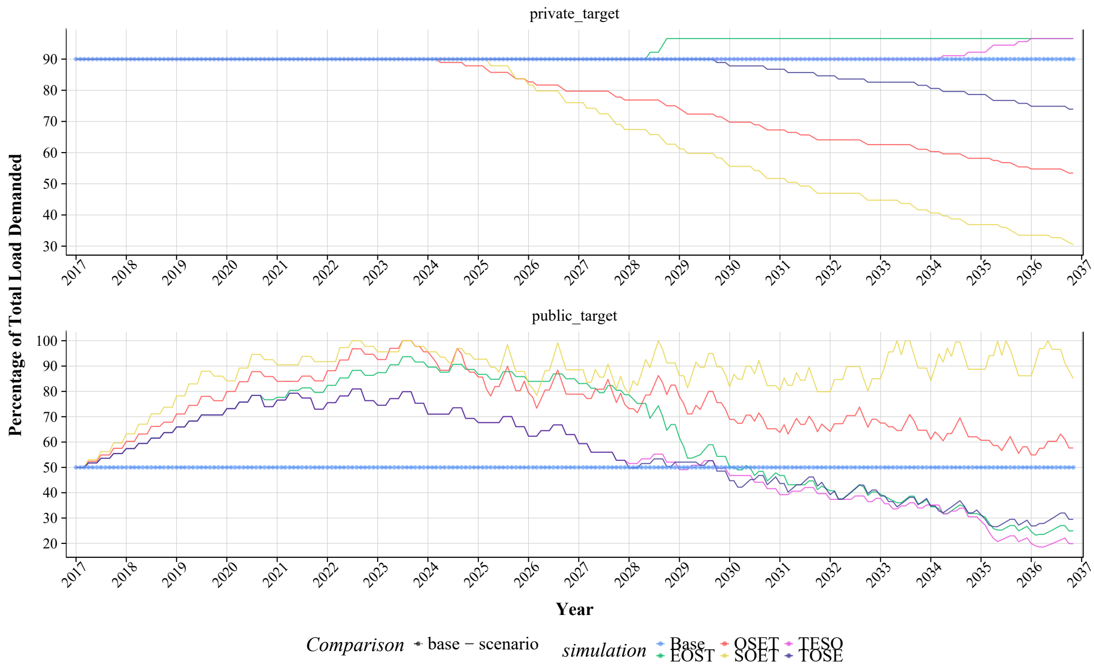

Figure 4.41: Target Availability - Multiple Scenarios

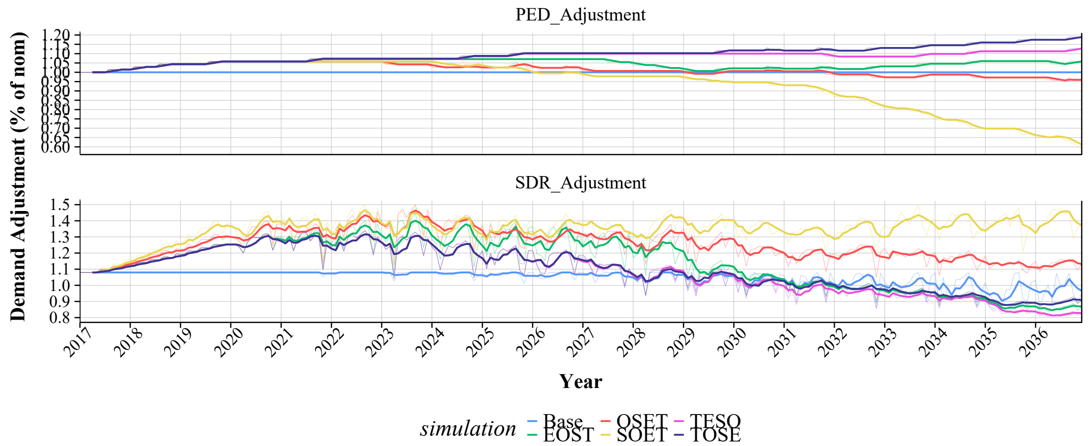

Figure 4.42: Demand Adjustments - Multiple Scenarios

Since all scenarios begin at a ‘medium’ skill level and 80% operational efficiency, training is needed to fully utilise the system generation capacity and to increase decision speed. As expected, OSET (#6) prioritised these investments, starting in year 3 and reaching maximum efficiency in year 7 as shown in Figures 4.43 and 4.44. Other scenarios have a lag in the start time for investments which are slower at reaching maximum efficiency as the investment size is limited by low prioritisation of the organisational decision set. TESO (#10), sets organisational decision at the lowest priority begins investing in year 8 and finishes in year 19.

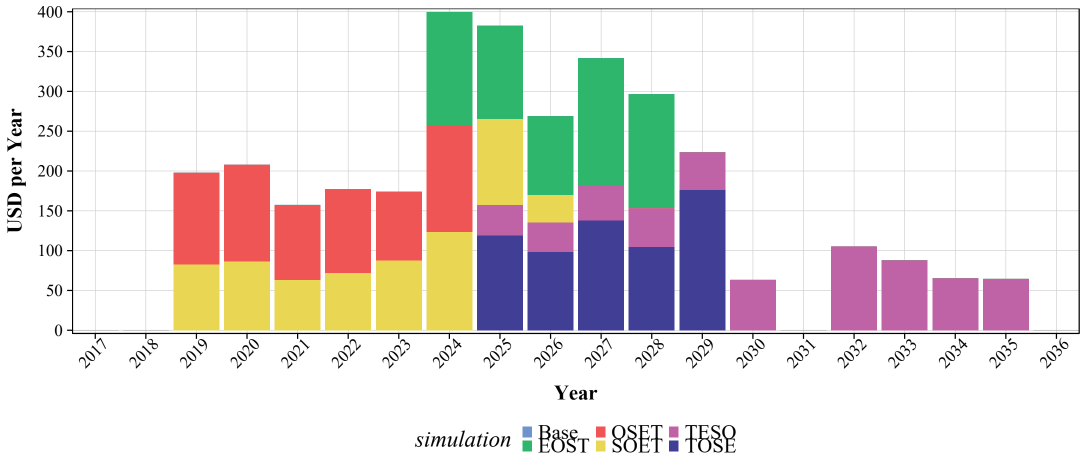

Figure 4.43: Training Investments - Multiple Scenarios

Comparing SOET (#7), EOST (#8) and TOSE (#9), which all have the organisational decision as the second priority, and investment in training is driven mainly by ability to make sufficient profits (over the monthly savings target). In the first 3 years SOET, raising the public target most drastically to nearly 90%, which increases private demand by + ~30% due to SDR and consequently produces a profit. Investment occurs over years 3 to 9 until maximum operational efficiency is reached. Meanwhile, EOST more modestly increases the public load target and only reaches sufficient profitability in year 7. For TOSE, which prioritises the technical decision set over the social set, public availability is a low priority and sufficient profits only come in year 8 when load growth accumulates anyway. This comparison reinforces the insight identified earlier that different decision sets are more optimal at different stages in the project lifespan. With multiple decision sets, it can be more precisely stated that prioritisation of decision sets at different stages is important.

Utilisation, shown in Figure 4.45, is both a critical indicator for decision-making and a result of those decisions. A quarterly average utilisation is shown for clarity,

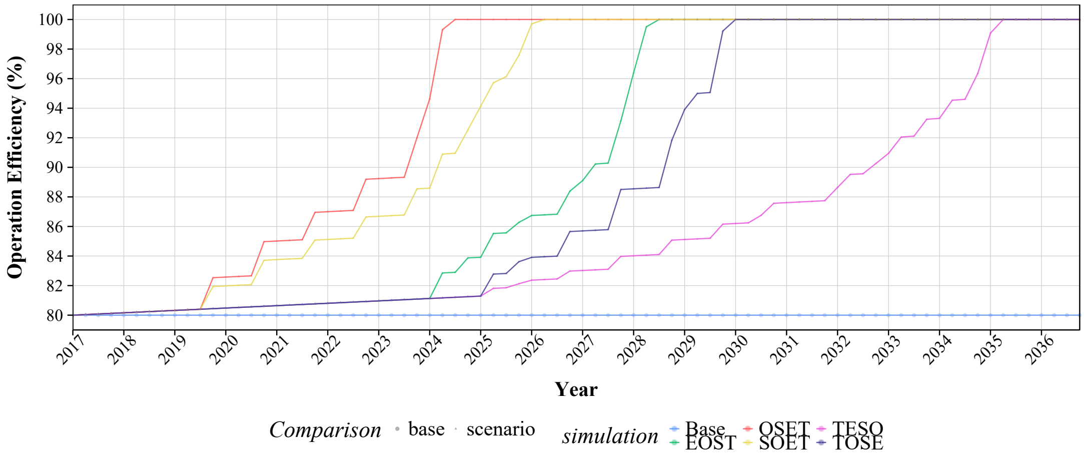

Figure 4.44: Operational Efficiency - Multiple Scenarios

though this reduces some of the extreme values. All scenarios besides the base scenario included the economic decision set and social decision set, both of which increased the public availability target. This was clearly important in the first 10 years as all scenarios achieved roughly 15-20% higher availability compared to the base scenario. Additionally, there is a noticeable gap of 5-10% utilisation between SOET, EOST, and OSET – the scenarios which most aggressively targeted public energy availability – and TOSE or TESO between years 7 - 12 as these scenarios targeted private energy availability. No scenario was able to achieve 100% utilisation despite targets to do so. OSET achieved 99.45% in year 14.

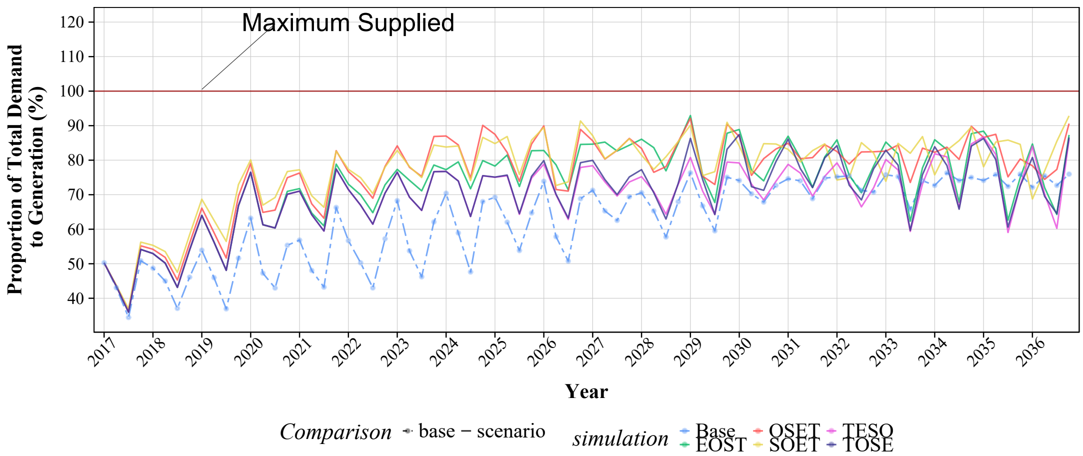

Figure 4.45: Utilisation - Multiple Scenarios

The simulated results of multiple decision sets have demonstrated the complexity of operations over a 20-year life-cycle of an off-grid PV systems in developing countries and the many potential outcomes that can result. In these simulations the order of decisions reflected priorities: in SOET (#7) public availability was around 90% of demand and public load served was the highest among the simulation group at: 480 kWh. Yet, its lack of priority towards serving the private load, exacerbated by pricing which further reduced private load demand, ultimately undermined the financial sustainability of the project as too few paying customers remained.

4.5 Chapter Conclusions

This chapter proposed a novel model for the simulation of the technical, financial, social, and organisational aspects of an off-grid PV project during a 20-year life-cycle. The decision sets and complexities were designed to be reflective of real-world projects that are documented as case studies in Chapter 3 and incorporate features such social demand response, price elasticity of demand, and operator decision-making that observe and respond to indicators – three novel features compared to the reference (techno-economic) model. Throughout the scenarios, the operational decisions proved to be critical to the outcome of project as did consumer and community decisions via PED and SDR effects.

Section 4.2 defined the model while Section 4.3 validated it against a HOMER generated reference model. Hourly solar generation and load were generated from statistical distributions of systems originally from Malawi. A component breakdown schedule covers the system solar panels, batteries, and converters (charge controller/inverter). A data overlay is implements following indicators: achieved availability of load, utilised energy, savings, and operator skill level. Four decision sets are created for an operator of the project to respond to the indicators – with each decision set targeting different sustainability aspects. Price Elasticity of Demand allowed for a variable demand curve and Social Demand Response, a new feature, allowed for customers to adjust their demand if the free public load (a social good) was being adequately supplied.

Section 4.4 discusses the results of the simulations. The performance of each individual decision set is compared against a baseline with no decision sets and evaluated against the following metrics: project balance, load served/not served and operating efficiency. The novel features of the model are reflective the complexities found in the literature, and, considerably impact the outcomes. The difference between project balances of the best and worst performing scenario were \$4,332 an -\$2,843. In addition, multiple decision sets are shown to have improved outcomes over individual sets over the course of the 20-yr simulation. There was evidence to suggest that adapting decision sets over the lifetime of the project may yield even better outcomes.

The immediate implications for modelling such projects are that techno-economic approaches are overly reductive of the context and therefore fail to predict sustainability problems. It is true that sustainability analyses stemming from techno-economic models are not expressly designed to address sustainability issues, but, as shown in the literature review, play a large role in how sustainability is planned for. In other words, despite its intention, techno-economic modelling is the defacto standard for sustainability modelling during the design stage of a project. New methods, such as the model proposed here, must be built and refined to incorporate important complexities such as operator decisions, load demand functions, and their interactions with a project's technical and economic performance. These can be 'layered' on top of techno-economic modelling to enable a more authentic simulation of sustainability issues.

For project implementers, where day to day operations and strategic monthly decision-making is a reality, the results justify further study into the factors touched upon in the model: decision-making rules, available information for those rules (i.e. indicators), and the mechanisms that can be defined and modelled (i.e. SDR). A major limitation of the sustainability model here is the limited empirical evidence supporting the modelling choices which limits its generality. Nonetheless, the observed results are true in their reflection of the case studies suggesting the groundwork laid here can be expanded upon with further evidence as it becomes available.

Policy makers can draw several important conclusions from the results of the simulation. First, the individual sustainability challenges that cause a project to fail are many, distinct, and inter-related. A project is not the sum total of a techno-economic optimal design, but can be complicated by non-technical and non-economic considerations have not been accounted for.

Second, projects can be heterogeneous in nature – one project may struggle with raising funds, another with impact, and another with acceptance and these may manifest at different times in the project life-cycle. The thesis model used a small set of parameters which represent a range of project characteristics. With this in mind, project, policies and regulations need to be flexible for different project arrangements. In other words, the bottom-up evolution of a project, stemming from its close connection to the community and the socio-cultural context, must not be suppressed by a top-down design strategy. Stakeholders are aware of the multi-objective nature of achieving project sustainability and the existence of a complex inter-dependency between sustainability factors. It is not enough to ensure the high reliability of supply if financial performance is poor. Nor will having a positive net income necessarily outweigh the importance of a good relationship with the community. A 'good' model must recognise that the modelled system, in this context, is more than a subset of parts that individually need to be optimised. The thesis model attempts to emulate this systems approach. As Ackhoff described in his explanation of systems as a whole made of parts: "[w]hen analysis reduces a system to its parts, it loses that system's essential properties. And when it considers the parts separately, it loses their essential properties. But if it considers the parts as parts of the whole-that is, their functions and roles in that whole-it can capture their essential properties and explain their behavior" [203].

Third, successful strategies which maximise the objectives throughout the project life-cycle, need stakeholder buy-in. Although in the thesis model the decision sets were fixed, the analysis of different scenarios (particularly the multiple decision set scenarios #6 - #10) supports changing priorities mid-stream when a given project is not proceeding sustainably. This could take the form of policy support, regulations, and skills-development. Underlying these aspirations is the need for a systematic approach to understanding sustainability of the projects themselves. Research, data collection, and analysis is needed to transition research efforts from the theoretical to robust evidence-based conclusions. Specific areas are discussed in later sections. However, continuation of the status quo that addresses sustainability only on the surface and is sometimes misguided, will open the door for repeated, poorly explained, project failure. Issues with sustainability frameworks including toolkits, indicators, and techno-economic design are evaluated against these implications in Chapter 5.

Chapter 5

Discussion

Previous chapters have provided evidence that the sustainability of off-grid electricity access projects remains an ongoing challenge (see Chapter 3). The approach to understanding these issues is inconsistent: off-grid sustainability toolkits have not consistently captured challenges and methods for measuring sustainability have been challenged in this thesis (see Chapter 2). Meanwhile, the model developed in Chapter 4 demonstrated how social and organisational aspects of a project could be incorporated and layered on top of an informational layer that is used for decision-making. The aim of this Chapter is to address the research gaps by proposing a framework to systematically improve design, implementation and learning around sustainability of off-grid electricity access projects in developing countries.

5.1 A Holistic View of Sustainability of Off-grid Projects in Developing Countries

Contrary to the design-centred view of project sustainability, this thesis presents evidence that supports a project life-cycle perspective, from design to operation to evaluation in which these stages are linked and equally valuable. Additionally, rather than weighting sustainability mostly on technical factors, both literature and modelling have reinforced the assertion that additional factors including social and organisational factors are important and also inter-related.

The critical analysis in this thesis has been valuable in order to expose the gaps in the sustainability literature:

- Inconsistencies in the understanding and definition of sustainability
- Methodological weaknesses of off-grid sustainability toolkits including: ambiguity of sustainability factors, limited evidence base for guidance, vague prescriptions, and an over-reliance on design stage sustainability planning
- Outcome-centric indicators rather than project-centric indicators
- Limitations of standard sustainability modelling methodology (i.e. to the consideration of techno-economic optimisation only)

Therefore, the purpose of this section is to propose a conceptual framework that seeks to constructively mitigate these gaps and criticisms. The implications for various stakeholders are then identified.

The proposed Sustainability Conceptual Framework (SCF) is shown in Figure 5.1 as a process map which captures sustainability planning and implementation at each stage in the project life-cycle. This framework conducts summative evaluations to compare a series of projects which leads to systematic learning, thereby incorporating the toolkit framework proposed in Chapter 2. The main innovations of the SCF are:

- Adoption of a consistent set of project-centric indicators during all project stages (design, operations, evaluation, learning)
- Project design modelling that integrates and simulates a comprehensive conceptualisation of sustainability factors and operational decision-making
- Formalisation of a systematic learning approach on sustainability within an improved toolkit structure

The value of the SCF can be explored and compared to the status quo by walking through the project life-cycle. A new project, shown in pink in Figure 5.1, is initialised from the current best practice model from sustainability toolkits, which can be assumed to contain the most accurate and comprehensive guidance on best methods, local knowledge, and the use of underlying data structure — indicators. New innovations that are attempted for any particular model are introduced during the project concept and

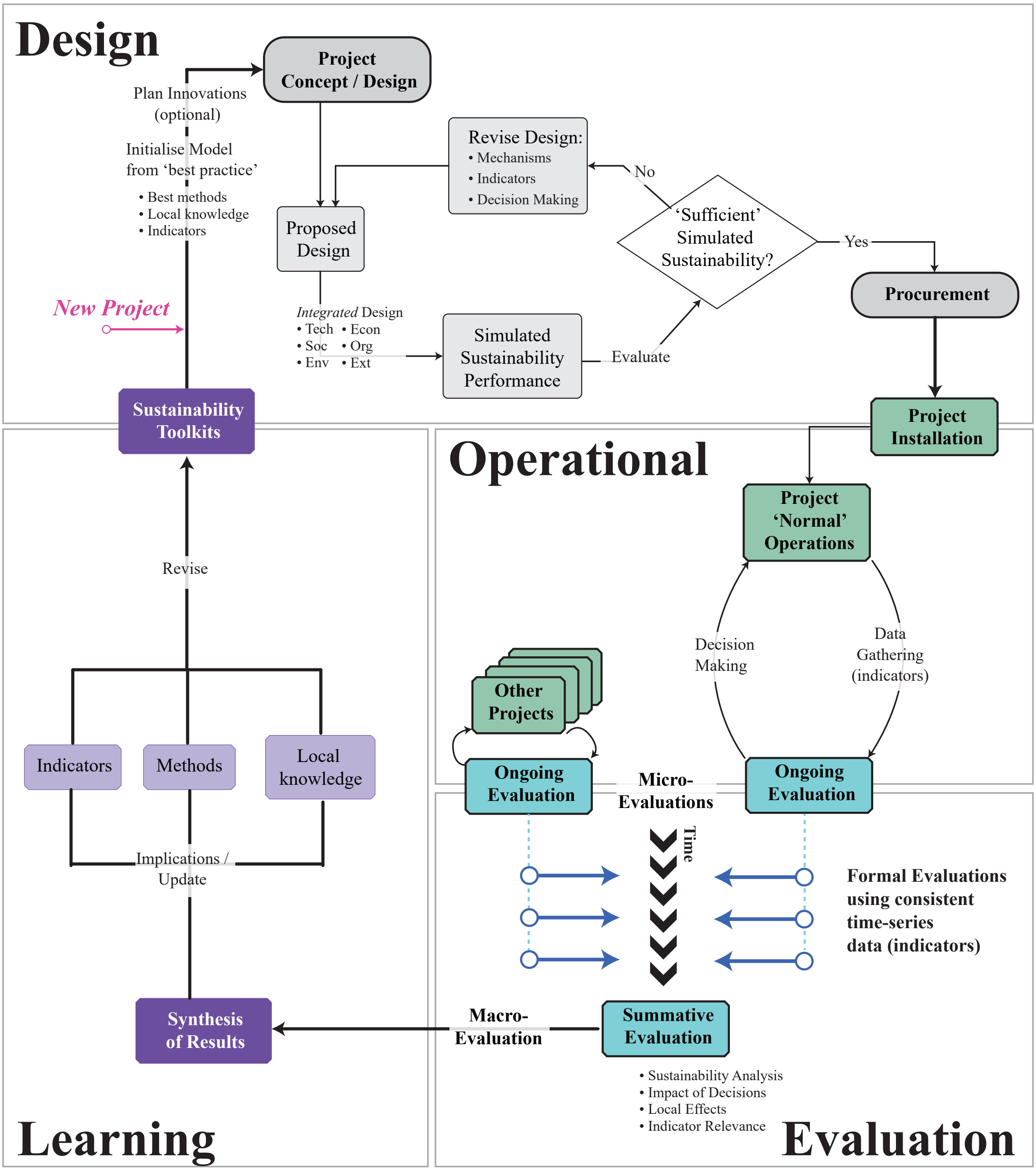

Figure 5.1: Sustainability Conceptual Framework

included and modelled during the project design stage. Examples of 'new' innovations are the use of a financing scheme deployed alongside the project or different ownership structures that prioritise decision sets differently.

The framework outlines an iterative approach taken to the **Design** stage that aims to achieve an acceptable level of (simulated) sustainability prior to moving on to installation. In the status quo, many software packages allow for the techno-economic simulation of a project during this stage, but have only limited design features to accommodate other sustainability factors. These other factors must then be addressed outside the model itself (if attempted at all). As an example, the improvement of operator skills may be identified but handled by providing a training session on site during installation. From a modelling perspective there is no mechanism to reflect this training. In the framework, the proposed design is considered 'integrated' as it explicitly requires that the designer address social, organisational, environmental, and external sustainability aspects (in addition to technical and economic) of the project such as community engagement, skills and training needs, and an approach to manage anticipated local ecological effects introduced by the project. It is critical at this stage that these aspects are articulated and can be incorporated into the design model, even if only a simple relationship can be established. Many such aspects have not be well defined in the literature; but new relationships could be incorporated more readily research progresses (see Chapter 7 - "Stress Testing" for a discussion additional features that could be modelled). The developer continues this loop until the design captures all salient sustainability aspects and has a reasonable expectation for (expected) project sustainability. Technical designs typically aim for a roughly 20 to 25 year life-span, following from the 20 to 25 year manufacturer specified lifespan of many solar panels. Since there is no agreed upon standard in the literature as to 'how much' sustainability is needed, in terms of years of likely survival, the technical target can be used as a stand-in.

A simulation of the project life-cycle implements the design in a controlled (virtual) environment and allows for the synthetic generation of the toolkit inspired indicators as the project ages. Although the model demonstrated in the thesis (see Chapter 4) expresses all sustainability factors explicitly in a single model, a hybrid approach which might consider several models separately and then analyse the aggregate results to arrive at a consensus is also valid. The results are assisted by modelling various scenarios especially around areas where the developer lacks information about the likely project conditions. In the thesis model, for example, this included parameterising the Social Demand Response (SDR) mechanism and initial operator skill levels. An analysis of the data-set for the indicators provides a basis to compare against past projects, where data and industry accepted sustainability targets are acquired from the toolkit, or are compared against the developer's own expectations. Using the same indicators for comparison even at the design stage, provides a common language and allows the developer to address the gap identified in this research, i.e. ambiguity of evaluation methodology. When the evaluation is complete, an objective decision can be made on the adequacy of the model to meet sustainability expectations. If insufficient, the project design process revises the design to address the weaknesses by re-characterising the mechanisms, adjusting the model of decision-making processes, or refining the underlying project arrangements. This cycle repeats until the project developer reaches a sufficient simulated sustainability level.

The framework purposely does not attempt to specify the exact level or minimum target to achieve 'sufficient' sustainability as this is currently not defined in the literature itself. However, over time as real-world data are accumulated and compared, targets could be supported by the work of those following the framework. Currently, sustainability targets have to be viewed as subjective and variable, as the definition of sustainability (at a project-level) has been conflated with impact targets. The thesis definition adopted in Section 2.1 could be considered here: duration in which the project can endure and/or survive within the local context. A time period from the point of commissioning, 10-/20-/x-years, could then be used as a target depending on whether the project was considered transitional (i.e. if a grid extension was expected by a certain date), or meant to operate indefinitely.

Simulation results in the design stage allow for an adjustment of key project parameters prior to installation, thereby increasing the likelihood of project sustainability. Procurement, which is highly simplified in the framework, follows an acceptable design and leads to the project being installed. Although the importance of a skilled, transparent, and efficient procurement process is of critical importance for projects of all sizes, the exact process is minimised in the framework to keep the emphasis on the relevant layers of a project development for this thesis: data, project modelling, and decision-making. Once the project is installed, the project enters the 'normal' operations stage and may lose added support from external organisations that help development up to that point.

During the **Operations** stage of the framework, business routines are handled by project management. Like many other businesses, day to day operations may include staffing, inventory, financial management, sales and marketing, maintenance, training, community relationship, customer service, and more. As an explicit part of the framework, a layer of data gathering based on the same indicators used during the design stage are implemented to assist in decision-making. Where appropriate, additional indicators should be added to assist in decision-making that are relevant to the specific context (business design and locale). For modelling simplicity, the thesis model reduced the day to day operational decision into a single metric, 'operational efficiency', which captured the skill and efficiency in carrying out these tasks. Decisions made at a strategic level such as pricing approach, financial planning, investing, human resource management also utilise the indicators, though perhaps less frequently.

As the project ages, many small scale or even informal evaluations take place, all leading to decision-making which then has a feedback loop to the normal operations of a project. Data gathering occurs at regular intervals and produces a comprehensive and coherent time-series data for the project. Although a data gathering regime is time consuming, it has lately become plausible due to new tools and the global reach of ICT [204]. The decision-making changes a project's business routines – for example, by changing a price, carrying new (or more) stocks of goods, taking out a loan, purchasing new equipment, or launching a promotion. The process repeats indefinitely for as long as the project remains active. While carrying out the process, it is valuable to capture both the indicators, used *a priori* for making decisions and *a posteriori* to appraise the effects of the decisions, as well as the details of decisions themselves. Singling out one or another simulation from Chapter 4, for example, demonstrated how a particular operator utilising a specific decision set goes on to impact the project sustainability. An extension to this model is where an operator has the opportunity to adjust the decision set, such as through prioritising decisions, which would represent an appraisal of the decision set.

The **Evaluation** stage of the framework implements a formal evaluation of the project at normal and meaningful increments. Additional input from policy-makers is needed to determine the appropriate increment, for example at 2 years, 5 years, and 10 years post installation. Formal evaluations are costly – typically involving external organisations – so the benefits need to weighed appropriately. Unlike the informal or micro-evaluations, the formal evaluation utilises all defined indicators and has a defined methodology.

The results of the evaluation are pertinent to the project itself summarise its performance under normal operations. When viewed from the wider perspective, evaluations of individual projects will always have a limited scope of relevance. However, assuming other projects produce similar formal evaluations, the opportunity arises to produce summative evaluations that do have broader relevance. An evaluation at this level incorporates sustainability analyses, research to determine the impact of decision-making, capturing of local effects that were relevant to a particular region or community for example, and reflexively assesses the relevance of the underlying indicators.

The **Learning** stage synthesises formal evaluation framework and makes conclusions on the results of the projects. A comparable set of time-series indicators for each project builds confidence in any material conclusions that are drawn on combinations methods and local effects that produced favourable sustainability outcomes. Finally, the indicators themselves are reviewed to confirm their relevance to sustainability evaluation, connections to important mechanisms that are observed, and revised if needed. The culmination of this effort is a general revision of the toolkit to incorporate what was learned through the formal process. In [165], the authors conduct an evaluation at a micro-hydro project in Nepal that reports both on the evaluation results but also the process of scoring. With the discussion, the authors raise the point that "it is important to identify high significant indicators" [165, p. 15] and revise weighting accordingly.

A template involving data, evaluation, and reflection on process is critical for improving upon evaluation methods. The framework proposed in this section is relevant for several main stakeholder groups throughout the cycle and indeed depends on each to continue to progress. The remaining sections of this Chapter identify potential benefits to these stakeholders and then goes on to discuss extensions to this work.

5.2 Benefits of Framework for Practitioners

Project designers, implementers, and practitioners are primarily concerned with adopting the most feasible designs and operational guidance to ensure the long-term sustainability of their project. While there may be some variation in priority of outcomes, such as different impact goals, sustainability of the project is a requirement in all cases.

The framework presented in this thesis provides a number of significant benefits to practitioners: scientifically supported best practice guidance, inheritance of tested indicators for performance management, a comprehensive modelling methodology to test assumptions before practical implementation and exposure to financial risks, and engagement with a learning community centred around the maintenance of the toolkit.

Scientifically supported best practice guidance from the framework can be contrasted against currently available toolkit guidance. In Section 2.2, it was argued that the guidance in current toolkits could be better connected to the evidence base. A major improvement in the framework is in the standardising of data gathering (indicators) and implementation of formal evaluations that can provide truly comparative analyses. This expands the effective evidence base – when more projects can be analysed and incorporated into toolkits, the recommendations will hold more weight. Project pitfalls and effects of innovations can be expressed through indicators. Furthermore, the framework also addresses the lack of focus on sustainability decision-making that could be made during a project's normal operations.

Indicators are used throughout the framework. They are simulated within design iterations, implemented during operations and used for decision-making, and compared and reviewed when projects are evaluated. In Section 2.3, this thesis argued that indicators are transitioning towards a project-centric focus that should considered separate to outcome-centric indicators. The framework implements this paradigm. Practitioners need the curated project-centric indicators that can be used to predict future success or failure of a project in meaningful sustainability terms, and support performance based management of the project.

Project modelling occurs primarily in the design stage where design ideas are explored, optimal system component sizing is determined, and expectations for project sustainability are validated. Techno-economic optimisation modelling, typically with off-the-shelf software packages, is a defacto standard despite the major limitations discussed in Section 2.4. The extensive and continued use in project feasibility studies suggests a disconnect between system designers and implementors who must plan for and respond to range of sustainability factors as captured in Chapter 3. With the framework and modelling in this thesis, it has been proposed that the complexity of sustainability factors are incorporated into models and simulations so that practitioners can plan for and predict project sustainability. The benefits of incorporating social, organisational, environmental and external sustainability factors (as well as an expanded perspective of technical and economic factors) and operational decision-making will increase the relevance of the designs. The current paradigm separates techno-economic modelling with non-technical aspects, which must modelled in parallel to the techno-economic model (or not at all). Instead, added complexity should successively be added to project model; features such as customer price responsiveness, organisational arrangements, and operational decision-making are demonstrations of potential add-ins.

Engagement with a learning community by using the framework is more systematic than that observed in the literature, where a wide range of sometimes incompatible indicator methodologies have made project comparisons difficult. The framework insists upon the use of standardised indicators throughout all stages of the project and envisions comparative analyses at various stages in the project life-cycle. In addition to the direct impact on project sustainability, the indicators can become a common language to interpret results and participate in wider scale evaluations. This promotes the possibility for more detailed and accurate comparisons between the sustainability of different projects.

5.3 Benefits of Framework for Research

Research in sustainability of off-grid projects in developing countries originate from perspectives of many scientific disciplines and are multi-disciplinary in nature given the primary importance of both physical systems, social systems, and human behaviours. The interrelationship of these systems are responsible for the complexity (and challenge) of ensuring sustainable outcomes for the underlying projects. The goals of this research is ultimately to influence policy makers to make evidence based policy and support practitioners, including communities, non-governmental organisations, government, and private investors towards implementing sustainable off-grid projects in developing countries.

Given the wide contributions in the literature, it is worthwhile to define a broader research objective for researchers concerned with project-level sustainability. First, there remains a need to define what components make a given project sustainable and under what circumstances and in a timely manner. Critical questions include: how can external conditions (to a project) be modelled and made relevant for each context – such as in a particular region and project ownership arrangement? How are key operational and investment decisions made using the data available, what impact do they have on sustainability metrics? How are underlying mechanisms in a project accurately identified, modelled and planned for – such as social support, elasticity of demand, theft, and operational efficiency?

In pursuit of these broader research questions, the research in this thesis offers some immediate challenges for researchers.

First, as has already been argued from other perspectives, sustainability modelling, currently dominated by techno-economic optimisations, needs to be extended to include other domains that are relevant to projects. Techno-economic optimisations, are not necessarily compatible with sustainability planning for which they are often used. As previously discussed, this is mainly due to the criteria for measuring a project's success in terms of its sustainability don't actually feature in these techno-economic optimisations. Examples from the proposed model in this thesis were highlighted with the impact of variable pricing on demand, a social support mechanism (though a social demand response function), operator decision-making, and operator skill levels. All of these mechanisms were motivated from challenges observed in real projects and were shown to have the possibility of strongly influencing the technical and economic performance of a project, and ultimately project success in terms of its sustainability. Sensitivity analysis around the social demand response (scenarios 11 - 14) had an end-of-project (20yr) difference in balance of over $7,000 and was the difference between financial success and failure. One approach would be to expand the class of model from this thesis, which parameterises these emergent mechanisms and defines mathematical relationships that bridge the project domains. The advantage during design is that variations can be made between each design iteration on these parameters and underlying relationships based on new information about the exact location and conditions on the ground. Project design is dependent on this information and often becomes available concurrently through these design iterations. Second, further study is required to understand the emergent mechanisms themselves. The thesis model proposed an initial yet simple method for formulating the relationship between project and mechanism identified from literature and available anecdotes. Better formulation of existing modelling is one possibility, for example: What are the coefficients to social demand response and price elasticity and how do they vary seasonally and over the course of the project life-cycle? Additional mechanisms such as proclivity for theft, both internal to the project, and external (i.e. from the community), competitor entry and subsequent competition over market share, staffing turnover, and maintenance cycles were left out of the thesis model for simplicity, but are thought to be influential on project sustainability and could be incorporated. Careful formulation of the mechanism is important, in particular its position endogenous to the project or exogenous. An example of initial steps towards better understanding the emergent mechanisms can be found in the study by Riva et al. where the authors develop causal loops between a electricity demand and various social impact areas (such as health and education) [205]. The study captures the complexity of local socio-economic systems that exist around off-grid electricity projects in developing countries. Such work could be leveraged as a basis for adding further complexity to the SDR mechanism that effectively links social outcomes to the project demand curve.

An additional area of interest is how to incorporate exogenous effects which can be critical to project success such as the local macroeconomic situation and directed support programmes (or lack thereof). The thesis model held much of the exogenous conditions in order to study endogenously modelled elements. Some aspects could already be handled within the existing model for example through higher initial consumer demand expectations, revising the cash flow to incorporate interest payments, or setting an assumed operational efficiency and operator skill level (i.e. following a dedicated national training programme). Other aspects require further study and research to meaningfully incorporate in such models: competitor entry and market participation requires expanding the demand model to accept non-binary choices such as whether to buy from the project, a competitor, or substitute goods or services. Another example is the maintenance provision. The thesis model assumed instantaneous replacement of all components that reached end-of-life or otherwise catastrophically failed. More sophisticated modelling would entail defining the system commissioning quality as this relates to the expected breakdown schedule (and could include local market component quality, local standards of commissioning, and extent of the market for repair services). An embedded assumption in many projects, however unrealistic, is that it attains fully self-sustaining operations. In fact, operators often lack technical skills to competently manage every system repair and especially more critical repairs. A sensible approach to modelling this would be to define typical failure modes, allow for partial failures, and mean time to repair parameters associated with the local supply chain. An undeveloped market would be expected to have high transactional costs to bring inefficient labour to rural areas and requiring relatively long turnaround times to fix the technical issue. Both examples provided demonstrate how well known, but not regularly modelled, external mechanisms can play a large role in project outcomes.

Third, the framework raises the profile of operational aspects of sustainability including decision-making and interventions after installation has occurred. The status quo approach is based heavily on design aspects – after setting up the project, attention recedes and the actions made while a project is operationally active is not often studied. Central are questions around how operational decisions are made in a project: what data is available to make the decisions, and what is the impact of the decisions? Within the thesis model, it was shown that additional training to improve operational efficiency was a key element to the project's success. Post-installation interventions such as a management consultation could adjust decision sets and priorities, depending on the stage of a project, and help rehabilitate a project and put it onto a sustainable trajectory. While the value of these interventions are obvious, questions remain as to what operational interventions are most effective and when can they be appropriately timed?

Fourth, project sustainability evaluations require consistency and comparability between projects to create a more comprehensive body of literature in support of sustainable project development. While much of this thesis has focused on a definition of sustainability involving the ongoing survival of a project, overall the research community vacillates between this definition and a definition that prioritises international development objectives. It is argued in this thesis that to improve our understanding (and treatment) of sustainability of off-grid projects in developing countries, that a narrow scope to the definition is needed which is strictly relevant to the underlying project itself. The framework provides a process for systematic evaluation of project performance, using a consistent time-series data and criteria for ensuring indicators remain relevant. However, further research is warranted to better define systematic methods for evaluation and comparison of projects, which this thesis has only touched upon.

Researchers should aim to produce multidisciplinary, and systematic research in the sustainability of off-grid systems in developing countries that expands the objective literature base and, where appropriate, is ready to confront the popular narrative. The production of project time-series data and availability of evaluations of off-grid project experiences remains an ongoing weakness in the development community. Evidence presented in this thesis has offered another narrative – that lack of sustainability poses a major risk to the UN Sustainable Energy for All goals. Researchers should resist temptation to conclude that the sustainability problem has been overcome, despite the rhetoric. The trend of reduced prices of solar panels and battery storage do not obviate the issue, this thesis has shown that the complexity of all the interrelationships that come up in a project is the real challenge. Future research needs to focus on reinforcing an objective narrative of project failure and success.

This thesis has argued for rationalising indicators at the project-level (project-centric) and for a definition more strictly related to the survival of a project rather than using outcome-centric indicators. Documenting project experiences through project-centric indicators would be an immediate step towards rebuilding a more objective narrative. In this sense, the thesis framework supports a more coordinated consistent and scalable approach towards off-grid electrification efforts in developing countries. Regardless of use of specific indicators or exact method, researchers interacting with projects should embrace learning from failures, not just success stories, and collaborate to build a multi-disciplinary understanding of how projects sustain themselves. The perspectives of different colleagues (see Section 1.1: Motivation), was a critical awakening for the author of this thesis on the value of all these perspectives during a sustainability evaluation. Along this vein, it is critical that future sustainability research avoid perpetuating analyses that overvalue one discipline over another – and instead embrace the multi-disciplinary nature of this area of research.

5.4 Policy Responses to Framework

International and domestic policy makers in developing countries are increasingly open towards off-grid efforts to increase access to electricity, especially in rural areas. Unprecedented investments are needed to meet the UN Sustainable Development Goal (No.7) of universal access to electricity by 2030. Major efforts such as through government led initiative, private investment, or donor funding require sustainability of individual projects. This framework supports an enabling environment for the development of the off-grid electricity access learning.

Government decision makers responding to the SDG 7 must balance the varying needs of different demographic groups and industries between the array of available implementation approaches all the while respecting each practical context. Yet recent studies have concluded that reaching universal access will entail a substantial proportion of off-grid projects – the IEA forecasts almost 450 million will be connected by standalone or mini-grid systems [38,51, p.483]. Government adoption of the framework would include policy support for adherence to best practice designs, defining acceptable levels of sustainability (using specific indicators), supportive policy interventions in a project's external factors (many of which can be influenced by government), and participation in research programmes to maximise learning from project experiences. The greatest benefit to governments in adopting the framework will be more sustainable off-grid projects. Many governments desire to tackle rural electrification through off-grid means but lack a strong track record of success to justify large scale programmes. Very few public investment alternatives offer such a high potential impact on constituents as electrification. Achieving access to electricity can be truly transformative for households. On one side of the spectrum of readiness for scaling off-grid projects, countries with little experience can use the framework for guidance to instil discipline and direction on pilot and small scale-up projects. Countries with a history of off-grid projects can consolidate their past learning and build on this with alternative experiences from international sources and use the framework to justify policy decisions.

An aspiration of the development community has long been to more fully integrate private financing to address the electricity access challenge. Several barriers prevent this integration. First, with capital funding coming from international sources, the perceived risks of off-grid projects have been too high compared to alternatives. Second, private investment is discouraged by the long timeline to achieve positive returns from electrification projects that also require accompanying economic development to become viable. Third conventional financing opportunities offer better overall returns than off-grid projects. It is for these reasons, and the neutrality of money from international financing, that government, non-governmental organisations (NGOs) and multi-lateral agencies such as the World Bank are needed to invest in initial programmes designed for both impact and learning. Addressing all these obstacles is beyond the scope of the framework presented in this thesis, but it can be argued that it offers some value towards better integration of private capital. Projects implemented under the framework will genuinely utilise best practices available to the development community, which will be supported with a body of comparable evidence. With respect to high perceived risks, the initialisation point of a project can be standardised from a recognised and well supported toolkit. In addition, by implementing an information layer of a project will allow financiers to better understand risks of the investment. With respect to the long timeline for returns, presumably projects reach will be able to reach financial sustainability and go on to turn a profit more quickly. Returns on any privately funded project are intricately linked to concurrent management of the non-financial aspects of the project. Since the framework encourages a holistic management of the project, it is argued that negative outcomes are less likely and both impact and positive financial performance more likely. Unfortunately, the framework offers no direct solution to make the returns on the off-grid investment more attractive versus competing sources in purely financial terms. However, assuming continued interest by social-investors, who consider social impact as well as financial returns, the framework supports the premise that both goals can be targeted concurrently and investments de-risked.

The framework supports the continued role of NGOs leading investments into higher risk off-grid electricity projects. Gaps in understanding of sustainability, especially in various local contexts, manifest as gaps in literature and sustainability toolkits. NGOs operating in developing countries have a clear opportunity to provide systematic data from these contexts and share results so they can be synthesised within improved toolkits. This is a subtle but important difference from practitioners implementing scaled solutions with less design leeway. Generalising all NGO-based off-grid electricity projects is unfair, but the end result of many NGOs operating in the space without clear guidance, such as the framework, has led to an over-reliance on anecdotal evidence that does not provide strictly comparable results to other projects. Because NGOs are often involved in pilot programmes and are willing to make innovative design choices, it is critical that the successes and failures are properly and fully incorporated into overall industry learning.

5.5 Alternative Frameworks for Addressing Sustainability Challenges

The proposed Sustainability Conceptual Framework (SCF) proposed in this Chapter (see Section 5.1) is contrasted in this Section against alternative frameworks within found in the literature. The literature is identified for recent approaches to addressing sustainability challenges in off-grid electricity access projects in developing countries. A description of the journal and article selection process is provided, followed by the review.

The articles were selected if they are specifically related to sustainability frameworks of off-grid electricity access projects and programmes in developing countries. The search was conducted in Science Direct, IEEE Xlpore, and Google Scholar. Articles were included if they were published between 2019 - 2022 to include only recent updates. Key words that were used included: “sustainability”, “sustainability framework”, “survivability”, “off-grid”, “methodology”, “electricity access”, “developing countries”, “global south”. This yielded a 144 articles in Science Direct, 103 in Google Scholar, and 64 in IEEE Explore. These were filtered upon review if they did not specifically connected to development of a frameworks, or offer an extension upon a framework and were relevant to off-grid project sustainability. Within IEEE Xplore all but seven of the 64 articles were out of scope, with the majority of the articles found in the September 2019, Volume 107, Issue 9 Special Issue of the Proceedings of the IEEE which was specifically related to Energy Access issues. Articles reporting to HOMER system designs or implementation of existing indicator frameworks were not considered. After filtering from Google Scholar and Science Direct, very few of initial articles were considered in scope. Another general review of Google Scholar found additional articles in the MPDI repository. A summary of the final articles included in the review, by source, are shown in Table 5.1.

Table 5.1: Alternative Frameworks Literature review

Source	**# of citations**
Proceedings of the IEEE	4
IEEE Access	1
Renewable and Sustainable Energy Reviews	1
Applied Energy	1
Energies	1
Sustainability	1

The approach outlined by Bahaj and James sought to implement projects using the Energy for Development (e4D) research group approach [206, 207]. Key e4D concepts to enable project sustainability involve community ownership of projects, robust technical system design, and strong external support teams that extended beyond project commissioning – among other tenets. Four projects, located in Kenya and Uganda, utilised this paradigm and were later evaluated. Upon evaluation the researchers grappled with the need to adjust energy tariffs and related demand changes (the PED effect), a number of non-technical issues such as supply chain of equipment, and low levels of technical skill levels (24-hour remote support was needed). The approach is considered here as a framework as it demonstrates a project life-cycle that is captured in the website and associated article – from concept and design to implementation and learning. As noted, operational issues highlighted in the SCF were present, further supporting the inclusion of PED and training component within the thesis model. The framework nonetheless lacks a complete overview of sustainability issues, has only limited evidentiary support from a handful of projects, appears to not utilise defined indicators, or attempt to conduct standardised evaluations.

Another academic initiative attempting to consolidate learning, proposed by Nathwani and Kammen, are Energy Access Innovation Centers (EAIC), part of a larger as the Affordable Energy for Humanity Global Change Initiative (AE4H) [208, 209]. At the time of writing (2022) AE4H had 53 participating, although the full vision of EAICs and knowledge exchange activities have not yet been fully realised. However, EAICs are conceived by the authors as a potential vehicle to address electricity access gaps primarily through knowledge exchange activities that sit in between university research labs and local implementation networks. The initiative's aim are to "develop long-term strategies that will lead, over time, to full access to modern energy services for improved life quality and economic self-sufficiency" – which clearly intersects with project sustainability challenges [208]. Knowledge exchange activities consist of reports, summits, fellowship programs, funding sources, and market research. This can be considered as a framework, albeit one that places technological innovation and the building of expert knowledge as its top goal. Off-grid project sustainability falls under the areas of interest of this group, though does not reach the level of detailed modeling included in the thesis model and SCF, as the SCF is related specifically to off-grid electricity access projects and is agnostic to technological innovation. Capturing, storing and curated knowledge by a organisation such as EAIC could be considered an alternative method towards storing knowledge in toolkits, as proposed in the SCF.

Sheng et al. propose indicators that build upon the World Bank methods for project post-evaluation in the context for multi-energy infrastructure projects [210]. The evaluation is applied to different stages in a project: project design, construction implementation, project operations, impact, and financial performance. The impact component captures contributions to various objectives such as national, social, and ecological. Although the indicators are not specifically geared towards off-grid electricity access projects, the potential for capturing sustainability issues at multiple stages in a project life-cycle has some similarities to the SCF. These include: indicators targeted toward project operations ('*Operational Reliability*', '*Personnel Quality*', '*Management of Maintenance Cost*') and the differentiation between internal and external indicators. A new area is during the construction stage of a project, described as 'implementation' by the authors, where indicators could be used to validate the quality of project commissioning. The framework described by Sheng et al. prioritises an after-the-fact financial and impact evaluation the project rather than a holistic sustainability evaluation.

The motivation for Ustun et al. for proposing a standardised data systems for first-access electricity systems is the need for a reduction of project risks to that have been an obstacle to investor engagement [211]. Currently, the use of data that *is* collected is hindered both generally and for the organisations involved in collecting it: “no mutual readability, no large database from which to study and extract meaningful results. A more peculiar situation is encountered when a particular company decides to examine its own data after a couple of years of operation. They cannot understand the meanings of variables and their values, as the data collection system was set up several years ago. Lack of standardized approach to data collection and storage renders the collected data ‘useless’ ” [211]. Under the proposal, two broad categories of data would be collected – the first could be considered demographic and the second technical/operational data. The overall data requirements would support learning on business performance and support integration with advanced technology such as smart meters and home energy management systems. Related to the this work, Lee et al. discuss the values and risks for an enhanced data capture within electricity access projects, pointing out that a data-driven framework would need to negotiate the various stakeholders involved: users, micro-utility, researcher, and government entity [212]. The focus on data considerations by these articles adds an detailed perspective to the SCF notion of indicators – the SCF broadly defines the relevant criteria for inclusion (see Section 2.3) but only implements a small subset in this thesis. Historically limited data accessibility in remote regions of developing countries have restrained the availability of suitable performance measures. As ICT resources have grown in recent years, the potential for higher quality and quantity of data that could be within the context would support a more intensive data systems for project sustainability modelling.

Almeshqab and Ustun qualitatively review lessons learned from rural electrification experiences in eight developing or emerging economies, often consisting of multiple sub-projects [213]. The review finds common factors for success such as: a stable long-term oriented policy environment, a consistent technical support for operations, technological agnosticism, and using a suitable financial model for a given project type. Sub-guidelines and general considerations for each are provided under these higher level factors – aimed at the next iterations of designs. The review does not use standardised indicators to evaluate success and focuses primarily on recommendations that benefit the design stage of a project and policy considerations for national entities.

Additionally, the eight country experiences date from the mid-1990s to 2012, and while relevant are only a limited sample. In this sense the authors' approach follows that of the development of toolkits that build upon learning from a select cross-section of projects (see Section 2.2). Utilising indicators would potentially make the results more quantitatively comparable within the included projects as well as others outside the study.

A resiliency framework is developed by Mazur et al. has some overlaps with project sustainability of off-grid projects in developing countries [214]. The framework draws from academic, national labs [215, 216], government [7], and consultant frameworks [217]. The term resiliency, used by the authors, is broad and covers a wide range of situations that could effect projects including for example natural disasters, changes in ecological conditions, cyber-physical threats, and political disturbances – to list a few. The framework further defines components of resiliency for power systems in particular and classifies them as: human, system robustness, reliability/adaptive capacity, efficiency, long-term strategic planning. Finally, a set of 42 indicators are proposed covering technical, economic, and social resilience. If indicators that are directly related to disasters are removed (i.e. '*Time to receive aid after disaster*' or '*Overall severity of impact*') the remaining indicators would be relevant to most normal state project operations (i.e. '*load factor*', '*local availability of tools*', '*revenue, profit*', '*existence of knowledge & skills transfer*'). Although the scope for the article is wider than the project-centric view of sustainability posed in this thesis, the article's framework includes a built-in reflection of proposed indicators that measure success (in this case for 'resiliency') similar to the indicator inclusion criteria proposed in Section 2.3. Therefore, resiliency framework could offer some complementary extensions to the SCF when considering low-likelihood or high-impact events that are captured in the broader resiliency scope.

A framework for project sustainability in Indonesia identifies high level challenges that are mapped to different project life-cycle stages [218] . The framework was informed by learning from fifteen remote Indonesian micro-grids that had experienced sustainability challenges. The authors propose using the ESMAP Multi-tier framework [7] as a starting point for evaluating project attributes over this timeline. Identified challenges are mapped to a classification of sustainability falling into familiar categories: institutional, social, technical, economic, and environmental. These are also mapped, alongside the ESMAP metrics to life-cycle stages going from planning to design and implementation and operation and maintenance. Further dis-aggregation of these stages are specified such as the demand forecasting, financial modeling, and environmental impact assessment – all falling under *planning.* Although there is no articulated learning component of the framework, it does make some suggestions to the status quo policies for development – for example, by offering critiques for system design sizing as implemented by the national grid code. The method suggests expanding the SCF sustainability modelling with more granular design stages than originally proposed.

Akinyele et al. offer a limited extension to HOMER outputs in sustainability planning by integrating additional (social and policy) dimensions [219]. A custom simulation is developed involving HOMER and additional analysis in Microsoft Excel that targets sustainability parameters under the high-level dimensions of social, technical, economic, environmental, and policy (STEEP) for long-term project viability. Primarily, the method uses a HOMER output to theorise about impacts exogenous to the model, which the authors concede needs further development. For example, with respect to the project's ability to provide all potential user load, two solutions are suggested such as grouping consumers together to better understand load requirements, and, using subsidies or incentive mechanisms to address shortfalls (in paying for the system). As a result, there remains a disconnect between the techno-economic simulation and new components of the simulation that must be qualitatively handled. Nonetheless the paper offers an extension to HOMER that attempts to address sustainability more holistically by tracking a wider set of output parameters similar to, but less integrated to all sustainability factors, the general approach taken in the thesis simulation. The method provides another perspective that supports a research need to extend the defacto standard modelling tools for system design.

This Section has reviewed recent project sustainability frameworks that have been published in the literature and compares the approaches to the Sustainability Conceptual Framework (SCF) proposed in this thesis. Additional frameworks are listed below with a summary of their connection to the SCF:

- Project development approach that acknowledges operational issues: validates inclusion of PED effect and skill levels.
- Creation of Energy Access Innovation Centres (EAICs): alternative to toolkits for sustainability knowledge repositories.
- Data standardisation: data-centric view that would support more detailed modelling of business performance.
- Toolkit refinements: additional detail such as including the construction process and other design stage sub-steps.
- Techno-economic application to social and policy components: validates research need to extend modelling tools.

Overall these additional frameworks are complementary to SCF, but typically have different scopes (i.e. relevant to the evaluation stage or learning stage) and in some cases have different but overlapping focii (i.e. resiliency vs. sustainability). The SCF is unique to combine a consideration of sustainability in multiple stages of the project life-cycle, a holistic understanding of sustainability factors, an information overlay (indicators) that drive sustainability decision making and evaluations, and an accumulation of knowledge into 'toolkits', as outlined in Figure 5.1.

5.6 Chapter Conclusions

This Chapter proposed a conceptual framework for off-grid electricity access project sustainability that integrated the advancements within the thesis. It has described the usage of the framework through the stages of a project life-cycle and explained the innovations that can improve the sustainability of projects. Adopting the framework offer a variety benefits to different stakeholders, each of which are identified and discussed.

Section 5.1 explored the framework at each stage in the project life-cycle. At a high-level, the framework is supportive of systematic learning on sustainability as it seeks to implement standardised indicators that are used in all stages of the project. In the design stage, indicators are used as an informational layer for simulations. This allows for more holistic models (as per Chapter 4) that include operator decision-making and enhancements beyond those typically included in techno-economic optimisations. The same indicators can be applied after a project has been commissioned and transitioned to normal operations. At this stage they become key performance indicators that drive operator decision-making. As a project progresses internal ongoing evaluations and strategic decision-making occurs. The status of the indicators and the decision-making that leverage the indicators are of interest from a learning perspective. In addition, summative evaluations at key project milestones (typically years of operation) can be gathered and compared against other projects. In other words, there is a macro-evaluation of results that utilise a common language, the indicators, and therefore have a broader relevance. Toolkits are then revised with a synthesis of results while also reflecting upon the suitability of methods and indicators used to draw conclusions. As a 'living' document, toolkits simultaneously serve the roles of capturing past learning, organising guidance, and being a common point of initialisation for new projects.

Section 5.2 discusses the benefits adopting the framework for practitioners who are primarily concerned with adopting the best possible design and implementation strategies for their projects maximizing project sustainability. It is argued that unlike the existing toolkits, a toolkit that is initialised from the framework is better connected to the evidence base, standardised around a common set of indicators, and robust in its recommendations of best practice. Furthermore, by insisting upon a holistic view of sustainability and the adoption of indicators, it presses practitioners to challenge their designs and tools that are used to plan and implement projects. This provides a strong basis for project comparisons that aid in overall learning for the practitioners themselves, but also for the community as a whole.

Section 5.3 proposes broad research questions following the insights found in the thesis and argues for extension of the innovations found in the research. A case is made for the for thrusting sustainability modelling outside the box of techno-economic optimisations and specifically into areas known to be relevant to project sustainability. Several novel mechanisms (price elasticity of demand, social demand response, and operator skill level) are demonstrated in the thesis model and were shown to be more reflective of actual projects and produce significantly different results from a reference model. Better understanding is needed of emergent mechanism (both endogenous and exogenous to the project), how they can be related to a project operations, and meaningfully incorporated into models. The inclusion of operator decision-making in the thesis model is a major novel contribution and opens the door for a realistic perspective of how a project behaves strategically to manage its sustainability. Sustainability planning no longer needs to follow the 'sustainability-by-design' philosophy.

The discussion in Section 5.4 considers how the UN Sustainable Development Goal 7 and the practice of the development community could benefit from use the framework. SDG 7 targets 100% electrification and off-grid sources such as solar home systems and micro-grids will be a core component of ability to meet the goal. Project failure, due to unsustainable operation, will directly undermine the goal and it has been shown in Chapter 3 that off-grid project sustainability should not be taken for granted. Furthermore, the analysis in Chapter 2 captured the inconsistent views of sustainability and challenged the methodology found in the literature for sustainability toolkits, indicator frameworks, and definitions of sustainability. A standardised framework that addresses these shortcomings is needed to efficiently pursue universal electrification goals. It was argued that a standardisation that resulted in more robust handling of sustainability throughout the project-cycle could support better coordination of investment sources.

Section 5.5 reviews recent project sustainability frameworks that have been published in the literature and compares the approaches to the Sustainability Conceptual Framework (SCF) proposed in this thesis. Additional frameworks are varied, including: the creation of Energy Access Innovation Centres (EAICs) as an entity to bridge research and learning and local experiences, an emphasis on standardisation of data in electricity access projects to extract meaningful learning and results, an implementation of potential indicators that consciously span internal versus external and project versus outcome, several methods to map identified sustainability challenges to project life-cycle stages, and a simulation method to extend the relevance of HOMER beyond its existing focus. Overall these additional frameworks are complementary to SCF, but typically have different scopes (i.e. relevant to the evaluation stage or learning stage) and in some cases have different but overlapping focii (i.e. resiliency vs. sustainability). The SCF is unique to combine a consideration of sustainability in multiple stages of the project life-cycle, a holistic understanding of sustainability factors, an information overlay (indicators) that drive sustainability decision making and evaluations, and an accumulation of knowledge into 'toolkits', as outlined in Figure 5.1.

Chapter 6

Conclusions

A better understanding of sustainability of off-grid electricity access projects in developing countries has been developed throughout this research. The review of literature has established that sustainability is a current and pressing issue for many projects. Despite the continued advance of technology, projects worldwide routinely fail to meet expectations due to a host of problems. Primary research from project in Gambia, Kenya, and Malawi delved into the challenges that have been poorly documented in the literature – issues of theft, community acceptance, dependence on external support systems, and limitations in local skills. This research has drawn attention to disconnect in learning on project sustainability, documented in the indicator framework and toolkit literature, and proposed a new framework that knits together different stages of the project: design, operations, evaluation, and learning processes. A new model was developed that allows for operational decision-making and demonstrates the value of relevant indicators that serve as the backbone through all stages.

These contributions are outlined in the remainder of the section, organised by chapter and highlighted for summary.

Summary of Chapter Content and Key Contributions

Chapter 1 describes the primary motivation of this thesis, efforts aimed at addressing the electricity access gap around the world and the ongoing sustainability challenges. This chapter includes a survey of international efforts, recent successes, extent of the problem, description of project components and stages. Despite the unprecedented desire to address the challenge, accompanied by massive investments, rural electrification of off-grid communities remains a considerable challenge both in terms of scale and process. Electricity access is core to human development and imparts tremendous benefits to the quality of life, availability of opportunity, and human dignity for the world's 771 million people, mostly rural, currently without access. It therefore stands to reason that improving access, namely by addressing the sustainability challenges that off-grid projects are facing, can help provide these benefits.

A review of definitions and efforts to measure sustainability are the focus of Chapter 2. The origins of the term are are found to be related to broad, global intentions although practical application to electrification project have adjusted its use. A nuanced project-centric definition is proposed and targeted to off-grid projects. In addition, the Chapter reviews several types of literature including sustainability toolkits, sustainability indicator frameworks, and techno-economic optimisations which have been prominently used to ensure sustainability.

Toolkits serve as a repository of knowledge on sustainability and, as they are compiled by organisations such as the World Bank, carry a lot of weight during project development. In the analysis, it was found that the main weaknesses of toolkits were that they have inconsistently defined and incorporated the concept of sustainability, have been overly dependent on the technical design stage of a project, are loosely connected to the evidence sources, and lack guidance on how to effectively measure a project's sustainability. Despite these gaps, the toolkit as a repository of working knowledge provides a critical role due to their prominence and potential for guiding the industry. A redesign of the toolkit is proposed which addresses these gaps and is compatible with project-centric indicators, a holistic understanding of sustainability, and relevant to the multiple stages of a project life-cycle.

Indicators frameworks have been applied to evaluate sustainability for electrification projects. One major strength is in their classification of interlinked relationships of a project into easy to understand categories (economic, technical, social/ethical, institutional, environmental) and evidence of their successful implementation in some off-grid programmes. This thesis critically reviewed the application of indicators and found both a continued use of mixed indicators (both outcome-centric and project-centric) and several innovations that demonstrated improvements towards stronger sustainability evaluations. Additionally, three critiques were argued against the use of outcome-centric indicators in off-grid project evaluations. This chapter identifies best practices with project-centric indicators and revises a criteria for indicator inclusion that addresses the gaps that were found and incorporates new innovations.

Techno-economic optimisations are heavily used in the design stage of a project to find the least-cost selection of electrical components while minimising capacity shortages. Use of prominent off-the-shelf software (such as HOMER) has had many benefits towards ensuring a project is on strong technical footing: best use of available resources, setting minimum reliability and carbon emission limits, understanding equipment procurement requirements, and ultimately to minimise costs. Although project sustainability planning is not primary purpose of the software, it is nonetheless pervasively used as such. Techno-economic analyses have become the defacto starting points for a project design although it must rely heavily on assumptions for non-technical interactions of a project. In Chapter 4, a novel extension to the project modelling approach was proposed which addresses these critiques by using a combination of a constrained scope techno-economic model with a new modelling methodology that explores more flexibility and realism in assumptions and operational level decision-making. This new model is the subject of analysis presented in Chapter 4.

In Chapter 3, the sustainability experience of past projects was reviewed and found a host of problems that contributed to project failures (i.e. component and system failure, unfeasible financial models, external issues, low skills, insufficient community involvement, etc.). Moreover, the inconsistency in which problems arise was argued to be an indication of the importance of the local context of each project, attributable to gaps in understanding and undervaluing of problems, and general lack of consistency in the learning process about sustainability issues.

In Chapter 4, a novel model is proposed to respond to the gaps and critiques that were raised earlier. The model compares outcomes from multiple scenarios over a 20-year lifespan. The results allowed for a more tangible perspective on several critical issues affecting sustainability. First, by relaxing the social, organisational, and economic assumptions which are inputs into techno-economic models, a wide range of scenarios and results were observed that the current dominant methodology has no means for explicitly modelling. The results have major implications on project sustainability and as a whole support evidence in the literature and case studies that sustainability is complex, highly inter-related, and context specific.

Second, by modelling the operational space, mainly by including operator decision-making and responsive consumers, the importance of the operational stage vis-à-vis project sustainability becomes critical. The model implemented an informational overlay for operators and consumers, in the form of indicators, that was found to be a critical the scenario outcomes. There is much anecdotal research that professes the importance of real-world mechanisms that impact project sustainability in this context, but it has not yet been explicitly modelled. Therefore, it is argued that the model here provides an initial framework that can be further refined as these mechanisms become better understood.

Next, the design, operation, evaluation and learning stages were connected through the various simulations. Design 'errors', such as a mis-identified social demand response, price elasticity of demand, initial skill level, and initial set-up of decision-making/priority, led to lowered potential sustainability, impact, and system availability. 'Optimal' operational decision-making was shown to be variable throughout the project, where in the initial stages an increased priority to increasing availability to the public consumer was beneficial but reduced financial viability in later stages. Different prioritisation of decisions at later stages performed better once demand was established and a degree of load growth occurred, suggesting an adaptable strategy to decision-making is needed. It is also useful to test simulations' results against the empirical data once a project is implemented. This would help answer questions around the relationship between indicators and decisions - such as when the decision is applied and what the its impact is on the project conditions. For example, if modelled as such, would 90% utilisation be a 'good' level to decide to reduce public load availability to, and would a 5% reduction in availability have a relatively small private demand response? Evidence at this level would help refine and adjust the understanding of the key mechanisms (such as demand response), the connections between an operator's decision and specific indicator, and project performance.

This thesis has made major novel contributions to the literature around defining and modelling sustainability of off-grid projects in developing countries. A wider appeal is made to practitioners who actively develop such projects to contribute to and develop a coordinated effort to produce systematic learning that is needed to make concrete strides towards consistent and widespread project sustainability. The framework proposed in this thesis represents a noteworthy, if initial, effort towards this goal. It is without a doubt that there are good intentions of off-grid project developers, communities, and individuals pursuant with the challenge of eradicating energy poverty around the world – to do so requires that they first achieve sustainability of the underlying projects.

Chapter 7

Future Work

The contributions of this thesis are to support a more systematic and coordinated framework for design, implementation, evaluation, and learning around the sustainability of off-grid projects in developing countries. This section introduces and discusses further extensions to this research programme either identified in the literature or as informed by the results herein.

Adoption of Project-centric Indicators in Evaluation

The practice of project sustainability evaluation requires standardisation to best combine qualitative data with the increasingly available quantitative data-sets generated as projects are installed and operated. As was documented in the literature there is currently no generally recognised method for evaluation which has led to weaker analyses and less comparability between evaluations.

Adoption of a common set of indicators would strongly support this goal but further research could be conducted on effective methods to compare projects. Questions following this line of thinking include: what data is gathered and how is it gathered? What is the priority of various indicators? What minimum sustainability levels (or indicator performance) are needed? How are conclusions can be drawn on the core causes of projects success and failure? These questions are driving towards the practical consideration of how project results are compared and disseminated to the wider stakeholder community.

As an initial recommendation, project implementors could implement the revised indicator criteria (see Table 2.5 in Section 2.3) for developing sustainability indicators. As a result, where there are similar indicators, a set of projects could have some comparability. Furthermore, gaps in the indicators implemented could be easily spotted. A sustainability evaluation of a single project would have more internal relevance. Additional coordination between evaluators of projects is needed for relevant comparisons to be made over wider sets of projects.

The prominence of existing toolkits and their issuing organisations could be leveraged along with revised toolkit. Re-orienting the toolkits for project-level sustainability and responding to the critiques noted in Section 2.2 could resolve the issue of coordination. These critiques were: lack of an evidence base to support its sustainability guidance, inconsistent specification of sustainability factors, low guidance around the interrelationship of sustainability factors, and an over-reliance on sustainability-by-design approach. Although the thesis has argued for changes to toolkits, wider stakeholder input and feedback is needed to produce further iterations.

Price Elasticity Modelling and Advanced Rates

When implementing Price Elasticity of Demand (PED) in the thesis model, the term was parameterised and held static throughout a given simulation. This was reasonable as PED is a new feature to be included in sustainability modelling and it was important to consider the model's sensitivity to PED variations. Future work should consider implementing a variable PED.

Implementing a seasonal PED would imply that the customers' willingness to purchase energy changes throughout the year. The exact scaling of very small off-grid projects must strike a balance between handling capacity requirements and minimising costs. The overall system capacity requirements are reflective of the peaking supply and demand requirement that ultimately define project scaling. Therefore, acknowledgement of seasonal PED would support seasonal rate designs to address peaking constraints (rather than a loss of energy). Filippinia and Pachauri provide estimates for summer, winter and monsoon seasons [190] which could be a good initial estimate until locally derived elasticities could be found.

Another alternative with further added granularity is found in Fan and Hyndman's elasticity study in South Australia [220]. They calculate price elasticity for seasonal periods and also at different demand quantiles, finding considerable variation. The Fan and Hyndman elasticity curve could be used to forecast potential price variations in different seasons alongside a load duration curve. The finding that there is relatively more inelastic PED during high load demand suggests time dynamic rate constructs (such as time of use or peak pricing) could achieve a more cost reflective revenue recovery.

Power utilities commonly separate rates by customer class (residential, commercial, industrial) to fairly reflect the underlying cost structure required to provide electricity service. Furthermore, it is reasonable to expect a different PED for different customer classes. This nuance could be extended to off-grid electricity access projects in developing countries by applying different PED to load classes. It may be reasonable to assume public consumers, such as health clinics, to be less responsive to prices than residential customers. Therefore, varying prices throughout the course of a simulation may impact demand differently depending on the different customer classes that are part of the project.

Differences in short-/long- term price elasticity could be reflected and would provide boundaries for price adjustments. Labendeira, Labeaga, and López-Otero conduct a meta-analysis on price elasticity of energy demand and find short term elasticity for electricity of -0.126 versus -0.365 for the long term [221]. Given this difference, pricing strategies that raise or lower prices over time could be optimised to maximise present value of the revenue streams.

In addition to more granular and potentially more accurate price elasticity modelling, the benefits of this modelling would be allow for adjustable pricing. Given the results of the thesis simulations, which found that the economic decision set was able to produce positive outcomes, further exploration of the value of advancing pricing is valid. This could be a valuable method to limiting risk of under-sizing, such as by implementing seasonal rates or time dynamic rates such as time of use or peak pricing.

Social Demand Response Modelling

The thesis model introduced a Social Demand Response (SDR), which provided a non-price based mechanism for customers to adjust their overall energy demand. Like PED, SDR term was parameterised and held static throughout a given simulation.

Another avenue for this mechanism is incorporating a probabilistic method for instances of theft, both internally (i.e. from employees) and externally (i.e. the customers and community). An assumption of probability of theft could be based initially on national or regional prevalence of theft (or crime generally) or from other projects. Parameterising the likelihood of theft could simulate impacts to sustainability in the design stage of a project. The causal factors of theft are not captured well in the literature, so future research could seek to better define a statistical model for prediction. In doing so, it is recommended to determine if factors that are endogenous to the project design (e.g. investment in security) and operations (e.g. community satisfaction with project) are relevant. If so, they could be implemented within a simulation, like the thesis model, that allowed for operator decision-making.

Community ownership structures for projects are another interesting area for SDR modelling. These are motivated as a way to instill local buy-in, ongoing support, and a stake in the long-term outcome of a project. However, some arrangements can become complex and introduce counteractive objectives to a project. Research is needed to support the careful modelling of the ownership structure and the implications it has on decision-making ability during the project design stage, particularly as it relates to the long-term financial planning of a project.

Staffing Considerations

Operator turnover and staffing was simplified in the thesis model by aggregating all non-technical losses into a prevailing operational efficiency parameter. A more detailed and realistic characterisation of staff skill and routine management is needed to better model off-grid projects in developing countries. Skill capacity limitations is perhaps the greatest weakness of projects today, yet its presence in modelling efforts is non-existent.

When projects are very small, in particular, potential operators must often be drawn from the local community, many of which have only basic education and many of whom, coming from a rural area with no prior access to electricity, are unfamiliar with the technology. Furthermore, the requirements of the position are potentially quite high: financial management, technical system operation, liaison with the community, stock management, sales and marketing, etc. Therefore, a more advanced model incorporating available skills capacity would involve the following elements: level and quality of training at the onset of the project, ongoing training provided, both technical and business related, such as long-term financial planning, customer relations, marketing and promotions, sales, technical operation, and investments.

Staff turnover is yet another reality of a project, as trained individuals that gain new skills can exploit opportunities these open up for them by moving to urban areas in the country where economic opportunities are typically higher (resulting in a so-called rural 'brain-drain'). This reasoning suggests that the relative value of skills in the local urban centres versus the salaries for operating the project should be taken into account.

Advanced Operator Decision-Making

Project stakeholder decision-making, in particular that of the project operator, is known to have a major impact on project sustainability. The thesis model demonstrated a subset of decisions: ability to adjust price, adjust supply of energy to various customer classes, and invest in training which were based on key indicators. The key innovation here is in overlaying the information layer and describing how the operator behaves in response to this information. From this base, research is needed in several complementary areas.

First and foremost is better understanding how decisions are made: what information is used, what options exist, and the range of actions taken. Out of necessity, the thesis model restricted the decisions to key areas, simplified the gradient of options, established some arbitrary boundaries around the range of actions taken. However, this was out of necessity; availability of supporting literature would have allowed for a more complete model of these decisions.

Second, further research into available project interventions is required, particularly in the life-cycle of a project *after* installation. This would open a new avenue of intervention for stakeholders such as government, NGOs, and research institutions to support project sustainability. Instead of a 'sustainability-by-design' attitude, policy makers could intervene to complement or correct the project's performance. In the short-term, the key questions are: which interventions are effective, and more difficult, when (and to what level) should supportive stakeholders intervene in a project? Examples may include, offering training to operations staff, community engagement support, or capital for system expansion. In the long-term, such post-installation interventions that are successful, should arguably be integrated into the wider supply chain, including potentially through commercialisation.

Optimising Operator Decision Set Strategies

In the simulation results, combinations of decision sets and relative prioritisation were found to be more effective than others at maximising income, energy supply, and system utilisation. The comparison of cases was limited to single decision sets and 5 variations with multiple decision sets – but once the simulation began, both the combination and prioritisation were held. For example, it was shown that the social decision set was important for early stages of a project when demand is low in order to establish a significant market size, but later tended to crowd out paying customers.

Further research could relax the decision set prioritisation constraint in order to allow the operator to adjust order of decision sets priority. This could be well suited to a hyperparameter optimisation with the order of decision set adjusted at periodic decision points. Better performing results would suggest operator timing for pivoting from one priority to another.

Another area of improvement would to utilise any locally estimated parametric settings for PED, SDR, and operator skill level. With a firm understanding of the local context of the project these inputs could be estimated through expert-interviews. Project demand and pricing data from existing projects to a proposed project (i.e. similar scale, same-country) could be leveraged to calculate PED. Although difficult to estimate, the exploration of initial operator skills with local stakeholders could be estimated through consultation. As a result, the simulation results would therefore be tuned to the local context and hence more relevant.

Scenario Stress Testing

The concept of 'stress testing' in this context refers to the introduction of more difficult assumptions into the simulation at the design stage and redesigning the project to better cope with the scenarios that have the highest propensity to occur. Using only the scope of the thesis model, situations like varied PED, extremely high negative SDR (penalty), and low skill levels were already demonstrated.

Additional scenarios such as high equipment breakage rates, high incidence of theft, high operator turnover, or reduced system efficiency or capacity factor could be modelled through a combination of probabilistic and deterministic methods. Equipment breakage in the simulation represented a single scenario drawn from a defined exponential probability distribution. Conventional distributions could be drawn where data-sets are more available (i.e. operator turnover), whereas Bayesian statistics with expert knowledge could be used to construct less well known distributions (i.e. theft). A probabilistic view of the full set of project assumptions and events that could occur throughout the project life-cycle may be worthwhile in terms of realism.

Simulated Decision Support Tool

Another extension of this research aims to run the simulation model alongside day-to-day operations as an operational decision support tool. This would help to overcome an individual operator's limitations in decision-making by adding more sophistication in decision-making such as through a forecasting functionality. The model could be re-initialised periodically, such as prior to a major decision point, using actual conditions to revisit potential challenges. In this mode the model is forward looking and could become a forecasting service.

Advanced decision support is also possible by establishing operational boundaries and programming preventative guidance to stay within those boundaries, for example by shifting available power between consumers, adjusting prices, or undertaking training. An interesting extension would be to provide a capacity within the model to simulate expansionary investments so the operator knows when it is prudent to do so.

Appendix A

Appendices

A.1 List of Abbreviations

Abbreviations used in this thesis are provided in alphabetical order below.

AC: Alternating Current

AE4H: Affordable Energy for Humanity Global Change Initiative

AFREA: Africa Renewable Energy Access Program

ANP: Analytical Network Process

ARE: Alliance for Rural Electrification

ARIMA: AutoRegressive Integrated Moving Average

CAPEX: Capital Expenditures

CEDP: Community Energy Development Programme

CES: Community Energy Scotland

CFL: Compact Fluorescent Lamp

CIGRÉ: International Council on Large Electric Systems

CO2: Carbon Dioxide

DOD: Depth of Discharge

DC: Direct Current

EAIC: Energy Access Innovation Centers

e4d: Energy For Development

ESMAP: Energy Sector Management Assistance Program

EUEI PDF: European Union Energy Initiative Partnership Dialogue Facility

GDP: Gross Domestic Product

GHG: Greenhouse Gas

GIZ: Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH

HDI: Human Development Index

HOMER: Hybrid Optimization of Multiple Energy Resources Software Package

IAEA: International Atomic Energy Agency

ICT: Information and Communications Technology

IEA: International Energy Agency

IEEE: Institute of Electrical and Electronics Engineers

IGA: Income Generating Activity

IRENA: International Renewable Energy Agency

KES: Kenya Shillings

km: Kilometre

KPI: Key Performance Indicator

kWh: kilo-Watt hours

KWH: Kilowatts for Humanity

kWp: kilo-Watts Peak

LCOE: Levelised Cost of Energy

LED: Light Emitting Diode

MDGs: Millennium Development Goals

MERA: Malawi Energy Regulatory Authority

MHP: Micro-hydro Plant

MPI: Global Multi-Dimensional Poverty Index

MREAP: Malawi Renewable Energy Acceleration Programme

MWK: Malawian Kwacha

NGO: Non-Governmental Organisation

O&M: Operations and Maintenance

OECD: Organisation for Economic Co-operation and Development

OPEX: Operating Expenditure

PED: Price Elasticity of Demand

PV: Photovoltaic

RECP: Africa-EU Renewable Energy Cooperation Programme

REFAD: Renewable Energy for African Development Model

REN21: Renewable Energy Policy Network for the 21st Century

SADC: Southern African Development Community

SAM: System Advisory Model

SCF: Sustainability Conceptual Framework

SDGs: United Nations Sustainable Development Goals

SDR: Social Demand Response

SE4ALL: United Nations Sustainable Development For All

SEP: Strategic Energy Project

SHS: Solar Home System

SMC: School Management Committee

SOC: State of Charge

SOGERV: Sustainable Off-Grid Electrification of Rural Villages

SREP: Scaling-Up Renewable Energy Programme

SSA: Sub-Saharan Africa

STEEP: Social, Technical, Economic, Environmental, and Policy

TOE: Tonne of Oil Equivalent

TVs: Televisions

UN: United Nations

USD: United States Dollar

V: Volts

WASHTED: Centre for Water, Sanitation, Health and Technology Development

WEO: World Energy Outlook

ZESCOs: Zambian Electric Service Companies

A.2 Full list of Sustainability Issues

Table A.1: Breakdown of Sustainability Issues by Category from Literature Review

Category	Count	% of total
Organisational	44	28.2%
Economic	25	16.0%
Social	34	21.8%
Technical	27	17.3%
Environmental	1	0.6%
External	25	16.0%
Total	156	100%

Table A.2: *Technical* Sustainability Issues found from the Literature. Proportions within category, of reviewed articles, and of overall mentions of sustainability issues shown in columns.

Theme and Item	Count	% in category	% of articles	% of total
Total	**156**			
Technical	**27**			17.3
under-sized system design	4	14.8	13.8	2.6
inability to manage growth / changes	3	11.1	10.3	1.9
low quality components (batteries)	3	11.1	10.3	1.9
unexpectedly high component failure	3	11.1	10.3	1.9
lack of maintenance systems	2	7.4	6.9	1.3
low quality components	2	7.4	6.9	1.3
low quality components (charge contr.)	2	7.4	6.9	1.3
poor installation quality	2	7.4	6.9	1.3
failure to follow technical stand.	1	3.7	3.4	0.6
low capacity factor	1	3.7	3.4	0.6
low quality components (bulbs)	1	3.7	3.4	0.6
low quality components (meters)	1	3.7	3.4	0.6
over-sized system design	1	3.7	3.4	0.6
poorly designed systems	1	3.7	3.4	0.6

Table A.3: *Organisational* Sustainability Issues found from the Literature. Proportions within category, of reviewed articles, and of overall mentions of sustainability issues shown in columns.

Category and Item	Count	% in category	% of articles	% of total
Total	**156**			
Organisational	**44**			28.2
after sales care / support	7	15.9	24.1	4.5
limited operator skill levels	5	11.4	17.2	3.2
limited local technical skills	4	9.1	13.8	2.6
operator ability to manage change / growth	4	9.1	13.8	2.6
low local entrepreneur involvement	3	6.8	10.3	1.9
complicated systems difficult to manage locally	2	4.5	6.9	1.3
non-payment	2	4.5	6.9	1.3
poor technology marketing	2	4.5	6.9	1.3
technician training	2	4.5	6.9	1.3
audit culture	1	2.3	3.4	0.6
cooperative ownership structure	1	2.3	3.4	0.6
customer friendly practices	1	2.3	3.4	0.6
dangerous operator working conditions	1	2.3	3.4	0.6
ineffective maintenance routine	1	2.3	3.4	0.6
ineffective project management	1	2.3	3.4	0.6
limited tools (analytics)	1	2.3	3.4	0.6
over-reliance on external support	1	2.3	3.4	0.6
poor ownership	1	2.3	3.4	0.6
Poor political support	1	2.3	3.4	0.6
poor project planning	1	2.3	3.4	0.6
self-organisation	1	2.3	3.4	0.6
temporary relationship between implementer and delivery org	1	2.3	3.4	0.6

Table A.4: *Economic* Sustainability Issues found from the Literature. Proportions within category, of reviewed articles, and of overall mentions of sustainability issues shown in columns.

Category and Item	Count	% in category	% of articles	% of total
Total	**156**			
Economic	**25**			16.0
unfeasible financial model	7	28.0	24.1	4.5
limited customer ability to pay	4	16.0	13.8	2.6
competition from main grid	2	8.0	6.9	1.3
IGA linked financial model	2	8.0	6.9	1.3
innovative / local financing	2	8.0	6.9	1.3
insufficient savings for future costs	2	8.0	6.9	1.3
competition from new technologies	1	4.0	3.4	0.6
expensive capital costs	1	4.0	3.4	0.6
low financing availability	1	4.0	3.4	0.6
low profit margins	1	4.0	3.4	0.6
unsubsidised financial model	1	4.0	3.4	0.6
warranty availability	1	4.0	3.4	0.6

Table A.5: *Environmental* Sustainability Issues found from the Literature. Proportions within category, of reviewed articles, and of overall mentions of sustainability issues shown in columns.

Category and Item	Count	% in category	% of articles	% of total
Total	**156**			
Environmental	**1**			0.6
inconsistent battery disposal	1	100	3.4	0.6

Table A.6: *Social* Sustainability Issues found from the Literature. Proportions within category, of reviewed articles, and of overall mentions of sustainability issues shown in columns.

Category and Item	Count	% in category	% of articles	% of total
Total	**156**			
Social	**34**			21.8
user skill levels	4	11.8	13.8	2.6
community participation / engagement	3	8.8	10.3	1.9
local ownership model	3	8.8	10.3	1.9
low user satisfaction	3	8.8	10.3	1.9
achievement of positive soc. outcomes	2	5.9	6.9	1.3
existence of trust	2	5.9	6.9	1.3
user & operator familiarity	2	5.9	6.9	1.3
user tampering	2	5.9	6.9	1.3
user training	2	5.9	6.9	1.3
appropriate to socio-cultural context	1	2.9	3.4	0.6
awareness of cultural attitudes	1	2.9	3.4	0.6
cultural tendencies (against savings)	1	2.9	3.4	0.6
dependence on subsidisation	1	2.9	3.4	0.6
lack of familiarity with local context	1	2.9	3.4	0.6
low community acceptance	1	2.9	3.4	0.6
over use of systems	1	2.9	3.4	0.6
poor ownership	1	2.9	3.4	0.6
public exclusion	1	2.9	3.4	0.6
un-supportive local power dynamics	1	2.9	3.4	0.6
user attitude	1	2.9	3.4	0.6

Table A.7: *External* Sustainability Issues found from the Literature. Proportions within category, of reviewed articles, and of overall mentions of sustainability issues shown in columns.

Category and Item	Count	% in category	% of articles	% of total
Total	**156**			
External	**25**			
enabling political environment	4	16.0	13.8	2.6
available spare parts	3	12.0	10.3	1.9
poor logistics	3	12.0	10.3	1.9
sufficiently developed supply chain	3	12.0	10.3	1.9
uncertain macroeconomics	2	8.0	6.9	1.3
corrupt awarding bodies	1	4.0	3.4	0.6
corruption	1	4.0	3.4	0.6
failure to follow technical standards	1	4.0	3.4	0.6
failure to secure land permissions	1	4.0	3.4	0.6
high capacity building requirements	1	4.0	3.4	0.6
high transport costs	1	4.0	3.4	0.6
Legacy of poor system design	1	4.0	3.4	0.6
low quality components	1	4.0	3.4	0.6
poor communications infrastructure	1	4.0	3.4	0.6
uncertain regulatory conditions	1	4.0	3.4	0.6

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