"Sustainable grid infrastructure: The co-Evolution of socio-economic and socio-technical systems through Micro-grid adoption"

By

Dustin Hayman

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Supervisor: Prof. Cristina Trois

Co-supervisor: Dr Claudia Loggia

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"EVALUATING BUILDING THERMAL PERFORMANCE AS AN APPROACH FOR A SMART ENERGY MANAGEMENT: THE RETROFIT OF AN OFFICE BUILDING IN DURBAN

C. Loggia, D. Hayman, Tramontin, C. Trois

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"SUSTAINABLE GRID INFRASTRUCTURE: THE CO-EVOLUTION OF SOCIO- ECONOMIC AND SOCIO-TECHNICAL SYSTEMS THROUGH MICROGRID ADOPTION"

D. Hayman1, C. Loggia*, C. Trois

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THE USE OF BEHAVIOURAL MODELLING TO DEVELOP SMARTBUILDING INFRASTRUCTURE IN SOUTH AFRICA

C. Loggia*, D. Hayman, V. Tramontin

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Date: 10th December 2015

Abstract

"Sustainable grid infrastructure: The co-Evolution of socio economic and socio technical systems through Microgrid adoption"

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Dustin Hayman

If our existence as a society, is within the bounds of a finite and dynamic environment; there exists and argument, that the ease of access to information has altered the search space within which our everyday reality operates. The purpose of this study is to align an enhanced understanding of Complexity science principles, towards the promotion of an alternative means of developing and understanding how the existing energy infrastructure functions. While simultaneously challenging the relationship between how, environmental (energy infrastructure) constraints, weather imposed or innate, relate to the internalities and externalities produced. An underlying aim and theme of this paper is the embracement of unavoidable environmental variations and how this can feasibly, and mutually aligns with the systems desire for structural rigidity, primarily through an investigation for the expansion of Microgrid development. The research focused on an existing medium sized commercial energy user in Durban with primary objective being the development of a deeper understanding of the case studies needs, as well as the potential role able to be played within the confines of the broader energy environment facilitated though an in-depth literature review on complexity science principles.

The dissertation consists of two primary sections, a literature review and a case study. The literature review provides an understanding primarily on sustainability; complexity, rationality and behavioural characteristics while the case study then attempted to, first apply this knowledge to an existing energy user, before theoretically highlighting the aggregation potential within the energy environment if these principles are applied to the macro and micro components of the energy system on a broader scale. In conclusion, Microgrid potential was clearly evident for an individual or business. However, this benefit can only be extended to the collective if accurate and real-time data is used to coordinate energy usage and renewable production, allowing seamless energy export to the grid at a higher net rate then is currently afforded was further found to enhance the viability of investment in renewable generation and storage. This decentralised approach was found to provide further incentive and control for municipalities to safe guard themselves against future shortfalls in supply. Above pure efficiency, a decentralised distributed system consisting of multiple sources creates a system which is highly effective and by extension sustainable.

Acknowledgements

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To My late parents, thank you for everything you did for me, I would not be where I am today if it weren't for you, and to Stephanie, Shirley and Farran, Thanks for getting me to the finish line.

Love you all.

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List of abbreviations

DOE	Department of Energy
vNM	von Neumann-Morgenstern Expected Utility Theory
RCT	Rational Choice theory
PD	Prisoners Dilemma
VCG	Vickrey-Clark-Groves mechanism
RET	Renewable energy technology
DER	Distributed energy resources
DO	Distribution operator
PCC	Point of common Coupling
LV	Low voltage
MV	Medium voltage
HV	High Voltage
CAS	Complex adaptive system
µgrid	Microgrid
EPU	end power user
NERSA	National energy regulator of South Africa
BESS	Battery energy storage system
ITOU	Industrial time of use
CTOU	Commercial time of use

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“Why don’t we turn the light bulb off?”

A Dilemma is a situation with two or more choices, Turning off the unnecessary light bulb became a dilemma when, within this small action, there existed the potential for individual interests to conflict with the interests of the collective. But why is this the case? Why does the logically superior choice have an opposing alternative in the first place? Perhaps the option of an inferior choice is the unique determinant within the social institution. If so, how did this unique determinate develop to allow deviation from what one would assume to be the singularly rational action? Darwinian thinking would imply that actions are a function of the past systems from which the current state progressed. Society appeals that we turn the light bulb off, playing on the conscience while neglecting the important attribute of man, he varies. This variation allows for a dominant determinate to be exponentially accentuated through successive generations. In nature the phasing out of an inferior determinate with that of the superior and desired trait, occurs over time, the greater the period of time, the greater the odds that nature would by that stage (with grave consequences) have counteracted the inefficiency.

In his book, *Situation Ethics: The New Morality,* Joseph Fletcher states that morality is *system sensitive;* Garrett Hardin further concluded that current ethical directives are out-dated in their exclusion of individual circumstances in light of the ever changing and inherently complex world today. Maybe the question in fact should not be focused on *why don’t we turn off the light bulb?* But instead be directed in asking *can the system react to not turning off the light bulb?* We exist within a welfare state, with each individual possessing equal right to the common (the common representing resources in all its forms) public interest in sustainability is created through this equality. But should we have equal right to the common? What if each social institution was entirely dependent on individually definable and quantifiable common. Would concern for public interest instead be replaced with an increased focus and understanding of the individual consequences of not turning off that light? Answering this question of why we do not and questioning the possibility for a system to evolve through individual actions, guided this research.

Chapter one: Introduction

1.1 Basis for the study

"It is essential that we overcome the "Tragedy of the Commons"

Which demands cooperation, even if this is achieved at slight detriment

To individual interests, our failure to achieve this will lead

To greater negative consequences for all"

- The Department of Energy (DOE), 2010

Tucked away in a report, the DOE's statement is sufficient evidence of why sustainability attempts will ultimately fail, particularly within the confines of the current framework of thinking. Acknowledging the notion that is, *Tragedy of commons,* while advocating that the solution has its basis in the demand of cooperation provisory to the altruist nature of man towards a collective common, hints at a fundamental lack of understanding towards exactly what *The tragedy of the commons* by nature is. Garrett Harden originally used the term in his 1968 work, which was rather simply titled "The Tragedy of the commons" here he used the phrase to describe situations representative of individuals who act independently and rationally, according to their own individual self-interests, and who behave contrary to the best interest of the group as a whole, through depletion of a common resource (Hardin, 1968). Linked to his work was the predominate idea of population growth. While not the subject of this research, the idea, and concept, of population growth is vitally important when aligned to our sustainability goals.

We arguably live in a finite world, thus able only to support a finite population. Longevity/sustainability in a Finite environment, implies a population growth of zero, for all intents and purposes the notion that population growth of the planet will eventually equal zero is implausible. However, assuming zero as a means to prove a point and the absence of a God affect, is the sustainability quest an achievable goal? Namely, is there a realizable goal in attaining the greatest good for the greatest number of people? The simple answer is no. There are two methods of validating this statement:

- Through the use of mathematics, in particular the theory of partial differentiable equations within which it is implicit that maximizing for two or more variables concurrently is an impossibility;

- The Biological proof from Harden's own thinking that life requires energy. Any energy above survival he termed work, work in this sense includes all forms of enjoyment. In order to maximize population, work energy must tend towards zero. Clearly it is evident that a requirement for maximizing population is the minimization of good. Hence it can be argued that the term *Optimum Good* would be more fitting in light of the frailty of a concept for *Maximum Good*. Thus potentially a requirement for the optimum good of the whole is the maximum good for the individual.

Herein exists another fundamental challenge in sustainability, primarily the fact that goods are incommensurable. What exactly is *good*? For individuals the notion holds vast variations. However, in real life settings the notion of goods is commensurable, in that there exists standards which individual good is measurable against (Garrett, 1968). This does not imply the same good, though it allows proportionality through *Proportional Good.* The morality of an act such as the proportioning and weighting of good is a function of the state of the system at the time it is in acted (Fletcher, 1966) in nature, natural selection is the determining factor, the overarching commensurate. The challenge as a society (global and local) is achieving a means of understanding and developing a means of weighting *Good*, in order to achieve the optimum good for the maximum number of people, whilst still allowing individuals freedom to do as they please. Creating a platform for individuals to realize their maximum good within the energy environment without negatively influencing the collective's rights is the guiding principles of this paper.

1.2 Research Question

In terms of meeting required environmental targets as well as energy supply security, is sustainability achievable through the facilitation of interconnected individual agents within an intelligent energy system? And is this distributed individualistic micro approach beneficial for the socio-technical system at the macro level?

1.3 Aims and Objectives

1.3.1Aims

The aim of this research is the formation of a deeper understanding towards the notion of sustainability in the current energy environment, so as to form a basis for challenging the classical operation of the current passive energy system in favour of a more dynamic, and adaptive one which promotes the effectiveness of individuals within the system, rather than pure system efficiency as the driver of sustainability objectives.

1.3.2 Objectives

1. Perform a brief and comprehensive literature review on the role of the agent in the current energy environment, in order to identify inherent weaknesses as well as highlight the existing latent potential for sustainability initiatives in the current structure.

2. Evaluate the process of green technology adoption for a consumer, in order to identify reasons for low adoption.

3. Investigate a feasible and viable mechanism for using individual agents as decentralized distributed producers of electricity, within the current grid structure.

4. Quantify the potential that exists in the LV grid consumers, this is hoped to develop a basis for justifying a focus on increasing levels of distributed resources.

5. Form an individual centric model showing how sustainability will be attainable with a move from the current rigid vertical passive system to a more horizontal active grid system. Proving a platform for future studies.

1.4 Methodology

1.4.1 Introduction

A theoretical qualitative approach was adopted throughout this research, primarily in the literature review chapters. An interdisciplinary approach was employed, relying on past research from multiple authors to form, first, a framework which guided the research, before providing the justification and motivation for observations and system challenges expounded as the research developed from concept to publication. A quantitative method was used for data collection in the case study, however the interoperation of the data relied on a qualitative assessment based on past and current research.

Justification for this approach is attributable to the scale of the research subject, the inherent complexity and large scale of the grid structure prohibits a true quantitative empirical approach at the level of this dissertation. Doing so, would result in a divergence form the initial aims of the paper and move focus from the macro structure of the energy grid as a whole, towards a primary focus on the micro components of the system structure

Focus one: Perform a comprehensive non-empirical, desktop study and literature review focusing on…

1. The role and place of Sustainability and sustainable development, primarily facilitating an enhanced focus of the role our energy systems play, in achieving the desired objectives.

2. Understanding Game theoretic principles, so as to provide a basis for proving how our current sustainability failures are a primarily a social problem

3. The role of Mechanism design in resource allocation, this chapter helps to form the notion that a bad system will beat a good person.

4. Understanding the idea that having Efficient consumers alone, is not enough, for a system to be sustainable, due to the system itself being unable to avoid problems generated through equal access to the common

5. Proving the idea that in a systems sense, being Effective, should be the over riding goal at the macro level. Having an effective system allows for the micro components to operate and function at a level optimal, not just for themselves but the collective as a whole.

Focus two: Developing a quantitative case study based on an existing commercial building in Durban, using qualitative research to analysis existing grid operation

1. Investigate Energy usage patterns and rates structure for renewable energy sources (RES) adoption

2. Summation of RES in the form of Solar PV and chemical storage systems focusing on the financial aspect and economic considerations. This was deemed to be the area of greatest inflexibility when it came to private sector adoption, and thus was a focus throughout the investigation

3. Investigate the process and benefit of the case study building moving to a Microgrid structure, fundamentally a qualitative discussion due to the limited time frame for the research, this process was achieved through a reliance on figures supplied from the

private sector and from eThekwini municipality

Focus three: A follow on to the investigation case study is a theoretical expansion on the potential of creating a sustainable intelligent energy system based around the aggregation effect of multiple distributed efficient buildings namely in terms of…

1. Distributed Renewable energy production potential in relation to an existing coal fired means, primarily with the focus on quantifying the scale of renewable adoption able to offset and replace traditional centralised methods of production.

The research ends with an extensive discussion and conclusion, which focuses on ideas and methods to address the current lack of sustainability and system effectiveness, providing a platform for further research and broader application to the current system.

1.4.2 Flow chart of activities

Chapter two: Literature review: The common resource problem and the drive for efficiency

2.1 Introduction

What improves the circumstances of the greater part can never be regarded as inconveniency to the whole. No society can surely be flourishing and happy, of which the far greater part of the members are poor and miserable.

The Wealth of Nations, Adam Smith 1759

Energy is an integral part of any developing economy, linked to the interrelated: economic, social and environmental aims of sustainable development, the triple bottom-line. At its core, Energy and its supply are explicitly linked to the enhancement in the standard of living for South Africans at all income levels. As population growth sores, so does the need for the acquisition of energy. This drive for energy produces the inescapable associated problem of its dissipation. Mitigating these effects is reliant on achieving more reliable and efficient access to energy for domestic consumption and production. However Governments' general response to energy issues has shown an inherent reluctance to create change within them. This in itself is a strongly worded subjective statement, proof lies in the observation that the department/bodies responsible for managing natural resources and protecting the environment are departmentally separated from those responsible for managing the economy or production of energy, holding separate mandates in accordance to their specific portfolios and jurisdictional scope. A segregation of Knowledge and skills occurs as a result. The challenges, and solutions, are both interdependent and integrated. Government's preference for integration into the energy environment, over increased interdependency of multiple agents within the energy environment will have an effect on energy reform. Understanding what differentiates integration and interdependence allows for a deeper understanding of the underlying nature of dynamic complex systems, which will be expanded on and discussed in relation to complex adaptive sociotechnical model development later on in the paper.

In governmental terms, this increased energy integration carries with it the connotation of the facilitation and expansion of trade in energy supply on the side of the state, with the gains from supply enhancing socio-economic welfare for the national as a whole, representative of a welfare state. Increased energy interdependence in contrast, has the consequence of creating more independent trade partners (SA citizens or municipalities), with aggregation of individual socio economic and socio technical improvements enhancing the broader economic and technical environment. Interdependency however, carries with it the correlated effect of increasing the risk of financial instability and potential reduction in state economic gains with further knock on effects such as a widening equality gap. This favouring of integration on the part of the state reduces the “transparency” of the energy market while increasing overall control, to this end there is also a need to balance the levels of integration and interdependency so as not to reduce governments ability to react to energy or financial crises through the implementation of national policies or action plans traditionally achieved through the neoclassical means of *command-and-control* or the *economic incentives* category. But what model is the current energy system truly representative of? Is there an alternative? Chapter four focuses on understanding the current system model which presents sustainable development as a societal issue. Highlighting that potential exists to achieve sustainability, however it will require changes to how we approach topics such as resource allocation and energy production providing. This provides the context under which the case study in the final chapters of Part I and II were based.

2.1.1 The shape of Energy Policies

In South Africa’s National Development plan are five key point performance areas, namely: (1) Basic Service delivery (2) local economic development (3) Municipal Institutional Development and Transformation, (4) Municipal Financial Viability and Management and, (5) Good Governance and Public participation. Whether implicitly or explicitly; within these five key performance areas energy has a role to play. From being a mechanism for social change to that of a mechanism for economic growth, the inherent importance of energy supply along with the associated consequences of that supply are directly linked to the idea of sustainability. There exists an inherent interdependency between the key point areas, inducing an added level of complexity in the relation between energy sustainability and task achievement. While the policies and developmental plans addressing them have differing overriding goals and overall focuses, there is prevalent and underlying theme of sustainability at the core of each of them. From these development plans there are five clear components of energy reform:

1. The need to improve energy investment;
2. The need for an increase in the adoption and diffusion of technological innovations;
3. An overall exponential increase in capacity expansion

4. The Restructuring and privatization of the energy environment;

5. The need for societal drivers.

There exists a relation, whether indirect or direct, between each component. This relation creates complexity, which is further enhanced when the individual agents within the system are modelled in a decentralized system. Chapter five deals with understanding and defining the agent within a system through mechanism design and place a focus on how individual goals can aggregate into potentially increased sustainability. The understanding of the framework required in attaining sustainability has been referred to, but what exactly is sustainability? And how does this definition and approach to sustainable development shape system outcomes?

2.1.2 Can sustainable development still guide policies?

The Brundtland Report of 1987 describes sustainable development as "*The ability to meet present needs without compromising future generations meeting theirs*" It hinted at the role of energy in stating how, "*A safe and sustainable energy pathway is crucial to sustainable development*". It further went to highlight the potential inhibitors to attainment, "*The substantial changes required in the present global energy mix will not be achieved by market pressures alone, given the dominant role of governments as producers of energy and their importance as consumers*" But how has the concept of sustainability and sustainable development progressed since then? Hopwood et al. (2005) would argue that sustainable development as a concept is in danger of becoming irrelevant. Irrelevancy created through how comprehensively the concept has been adopted in every facet of society as a means to attaining all that is good and desired. Its success in that respect has created an issue of an increase in complexity among its interrelated aims that it renders the concepts role within policymaking impotent. The terms, Sustainability and sustainable development have been used interchangeably throughout, sustainability is often referred to as a process, while sustainable development as an end state, however their scope and implications are one and the same and thus require the same concurrent level of discussion. Understanding the concept of sustainability is simple enough, yet there still exists a fundamental disagreement between scientist and politicians on the exact definition of sustainable development. Yet its persistence, as an ideological concept never ceases to diminish. Lafferty (2005) neatly highlighted this point when he highlighted how: sustainable development ''is now like 'democracy': it is universally desired, diversely understood, extremely difficult to achieve, and will not go away'' The aim of this study is ultimately achieving sustainable development, and one of the main objectives is understanding and defining sustainability as a concept and ideal, in order to reduce the complex nature of its successful incorporating within future energy models and policies. This definition and understanding is the prevailing theme of Chapter three, however each subsequent chapter embraces this deeper understanding and is used as a means of attaining this papers aims.

2.1.3 The Primary dimensions of sustainability, and the inconvenient secondary ones

‘‘*We act as we do because we can get away with it: future generations do not vote; they have no political or financial power; they cannot challenge our decisions*’’ (WCED, 1987, p. 8)

Holden et al. (2014) in their study of “*Our Common future”* identified a definition between primary and secondary dimensions of sustainability. Primary dimensions he termed as being, non-negotiable, ‘‘*fundamental objective values, not subjective individual preferences*.’’ (Daly, 2007) Secondary dimensions play a subordinate role to primary and thus in cases must give way to that of the primary. The four dominate dimensions are seen as: (1) Satisfaction of basic human needs (2) safe guarding long term ecological sustainability (3) The promotion of intra-generational and (4) inter-generational equity.

Høyer (2000) identified secondary dimensions, which included, among others, the preservation of nature’s intrinsic value, the promoting of environmental protection, promoting public participation, and satisfying aspirations for an improved standard of living (or quality of life). This subordinate view of secondary dimensions implies a challenge to the current dominant “triple bottom line” sustainability model, which aims at balancing economic, social and environmental dimensions. This subordinate view manifested itself in three unique ideas, which formed a basis when developing the model later in Part I and II. Namely that: Economic growth is not a primary dimension, and instead is a facilitating means to attain the four primary dimensions. Secondly, Participation and acceptance by stakeholders is not necessary for sustainability’s success, Contrary to Amekudzi et al. (2009); Castillo and Pitfield, (2010) and Shiftan et al. (2003) studies that consider this aspect crucial to attaining sustainability. It is agreed that acceptance and participation is needed in ensuring efficient implementation, but not subjectively reliant on local stakeholders chosen agreements. And, thirdly there exists a need for minimum and maximum thresholds, not relative changes. Holden et al. (2014) argued this point through highlighting that changing an unsustainable state to that of a less unsustainable state, through positive rates of change, is good but cannot as a result be considered sustainable. This will be graphically represented later in the chapter as a rationale for this research. This understanding of the primary dimensions and their relation to secondary dimensions highlights the complex nature of sustainability, providing weak justification for questioning the current energy model, but also how which component, or version of sustainability we adopt plays a role in shaping the energy model striving to achieve the four primary dimensions while balancing the secondary…

2.1.4 Strong vs. weak sustainability

The multi-faceted nature of sustainability poses an inherent multitude of problems, in the dominant traditional neoclassical economic paradigm; sustainability is logically represented as a quantitative understanding in the form of what is termed *weak sustainability*. Its antithesis exists in the form of ecological-centrism, or *very strong sustainability*, however the heterodox view of the neoclassical paradigm is that of ecological modernization, or *strong sustainability*, which emphasizes the qualitative side of growth (Neumayer, 1999) This qualitative aspect, within ecological modernization, is constitutive of the objectives of sustainability through its promotion of the efficient allocation of the common, and the inter-generational preservation of the natural environment. There is an argument for the weak and the very strong versions, however the arguments in favour of the less restrictive strong version outweigh both. The current economy has its basis in the weak spectrum of sustainability, in that it uses GDP's per capita growth as an indicator of welfare, which in the long term is inherently unsustainable (van den Bergh and Antal, 2014) In this weak version there is an implicit sustainability restraint present which poses a degree of restriction on resource using activities. However, these are not explicit in that they do not arise as a result of a concern for the ecosystem, rather it results from a fundamental concern for the ecosystem's finite ability to meet human needs (Holden et al 2014). Thus, this weak version allows for the substitution between all forms of capital resources, this is consistent with declining levels of natural capital being justified through an offset in other forms of manufactured capital. Balaceanu and Apostol (2014) neatly referred this approach as akin to the *more with more* view of an industrialised society, which needs to be abandoned in favour of *more progress with fewer natural resource* relationship basis between society and nature. The reintegration, of the economy and society, into the finite natural sustainability limits requires arguably the stronger version of sustainability. At the other extreme end of the spectrum, sits the very strong version, which explicitly concentrates on the relation between global carry capacity and the scale of human development. It holds the more prophetic view that when global carrying capacities are reached, substitutability will cease as a possibility, and human development would have reached its absolute limits.

This advocating of temperance and restraint goes against the understanding of sustainability when it sacrifices other primary dimensions in favour of the ecological primary, this is not consistent with the aims of sustainability in its purest form and thus for this paper and finding a shaping framework to guide the direction can be ignored. What are the alternatives then? Is it even possible to juggle the needs of society with the restrictive limits of nature? Adoption of a strong sustainability approach is perhaps the most consistent with the aims of sustainable development. Daly (2005) highlights the view of ecological economists that natural and man-made capitals are complimentary rather than merely a substitute for one another. This still poses the unavoidable problem, manifesting in our desire and pursuit for concepts, which are analytical, and operational. Contrastingly strong sustainability is normative and ethical (Dietz and Neumayer 2006). This problem exist purely due to the contrasting views between weak and strong, focusing on promoting the aspects which are related to development and quality of life contrasts with a focus on accumulating and consumption growth which internalizes benefits and socializes costs. This contrast and "battle" between the two views formed an ideological basis for breaking the current methodology towards sustainability and was implicit in the following chapters.

2.1.5 Graphical rationale

Understanding that weak vs. strong sustainability views hold differing implications and connotations for the concept of sustainability is a good starting point, however there is a need to justify a basis for a re-examination of our current path in empirical evidence, highlighting the direction we are heading in, particularly in relation to the primary dimensions of sustainability. The overriding rationale for this study can be justified through what Amekudzi et al. (2009) refer to as the *Sustainable development space, which* represents the threshold values for the four primary dimensions of sustainability. This requires indictors measurable against the primary dimensions, (Karlsson, n.d.) Used a single indictor and threshold value for each primary dimension, with the view that each is equal and non-tradable as a target. This is in contrast to that of the UN Commission on Sustainable Development (UNCSD, 2007), who had suggested a list of 96 indicators or the International Human Dimensions Programme on Global Environmental Change's Inclusive Wealth Index Those Indicators used are represented in the table below.

Table 1: Primary dimensions, indicators, and suggested 2030 threshold values for sustainable development (Holden et al. (2014)

Dimension	Indicator	2030 Threshold
(1) Safeguarding long term ecological sustainability	Yearly per capita ecological footprint	max 2.3hga per capita
(2) Satisfying Basic Human Needs	Human development index	min 0.630
(3) Promoting intergenerational Equity	Gini coefficient	max 40
(4) Promoting intergenerational equity	Proportion of renewable to total energy in primary production	min 27%

These thresholds and indicators for the four primary dimensions were developed as a means of tracking sustainability in representative and relatable terms. The Ecological footprint tracks humanities demands on nature in the form of consumption against natural regenerative capacities. The value is calculated through measuring the area required to produce what we consume, as well as calculating the area occupied by infrastructure and the area of forestry required sequestering CO_2 not absorbed by the ocean. Next, The human development index measures the level of basic human needs achieved, this composite indicator measures average achievement in human development, namely: Standard of living, knowledge and prosperity of life. (UNDP, 2011). Thirdly, The Gini coefficient is perhaps the most popular indicator today, measuring inequality.

Traditionally sustainability and normative models require equity and not equality balances. Equity refers to the qualities of virtues, while equality refers to the equal sharing of something: Sen, (2009) resolves this issue by highlighting that sustainable development as a normative theory of social equity, demands equality of something. Thus, Holden et al. view the distribution of income as an important measure of equity in society with a zero value total equity/equality and 100 expressing maximum inequality. Finally, intergenerational equity requires that future needs can be met by that generation, quantifying these needs are impossible however it is intuitive that there is an explicit energy requirement in meeting those needs. Fossil fuels will play a role in the future needs, thus preserving adequate levels is reliant on renewable production offsetting some consumption today. In fact, this proportion can be used as a sustainability indicator. Weaknesses exist within this methodology; however, in spite of these weaknesses the indicators are scientifically robust in providing a platform for analysis of current sustainability. There is one crucial weakness in particular with regards to land space, which provides a possible justification for adopting a decentralized multi agent system of microgrids.

Twidell and Weir, (2005) state that renewable energy production is up to 1000 times more spatially demanding than fossil energy production, meaning that an increase in the threshold indicator for primary four will impact the threshold value in primary one, thus high levels of renewable adoption would in essence be unsustainable in the very strong sense, these effects are accommodated for in the threshold value for the strong sense, but the notion highlights potential which exists in maximizing (or in some sense minimizing) our infrastructure footprint.

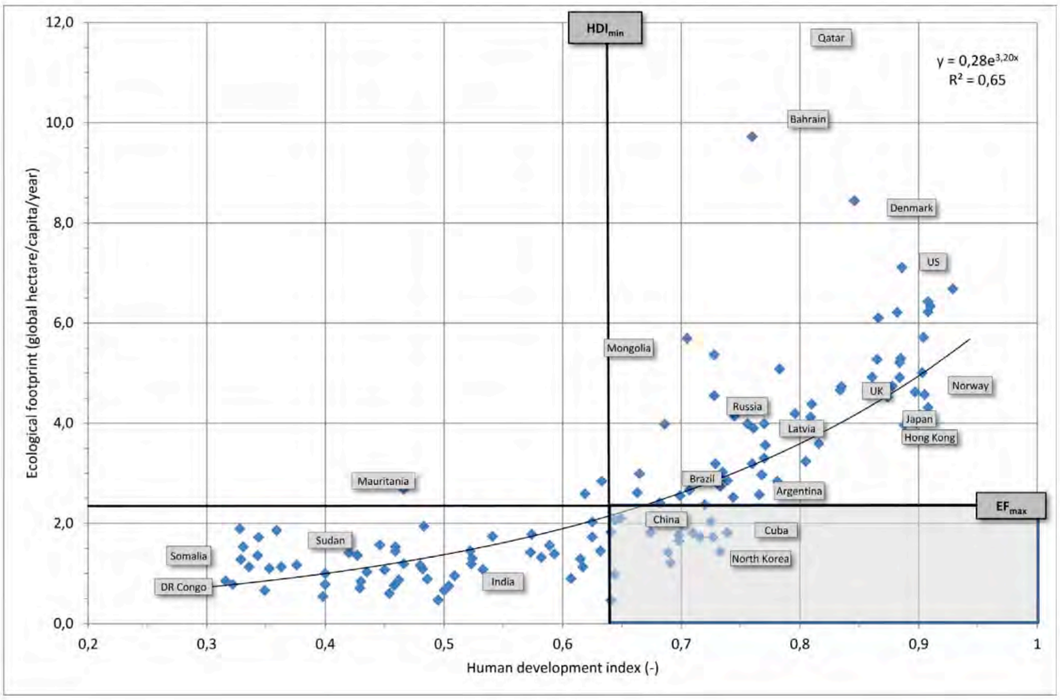

Figure 1: Relationship between Human development and Ecological footprint (Holden et al 2014)

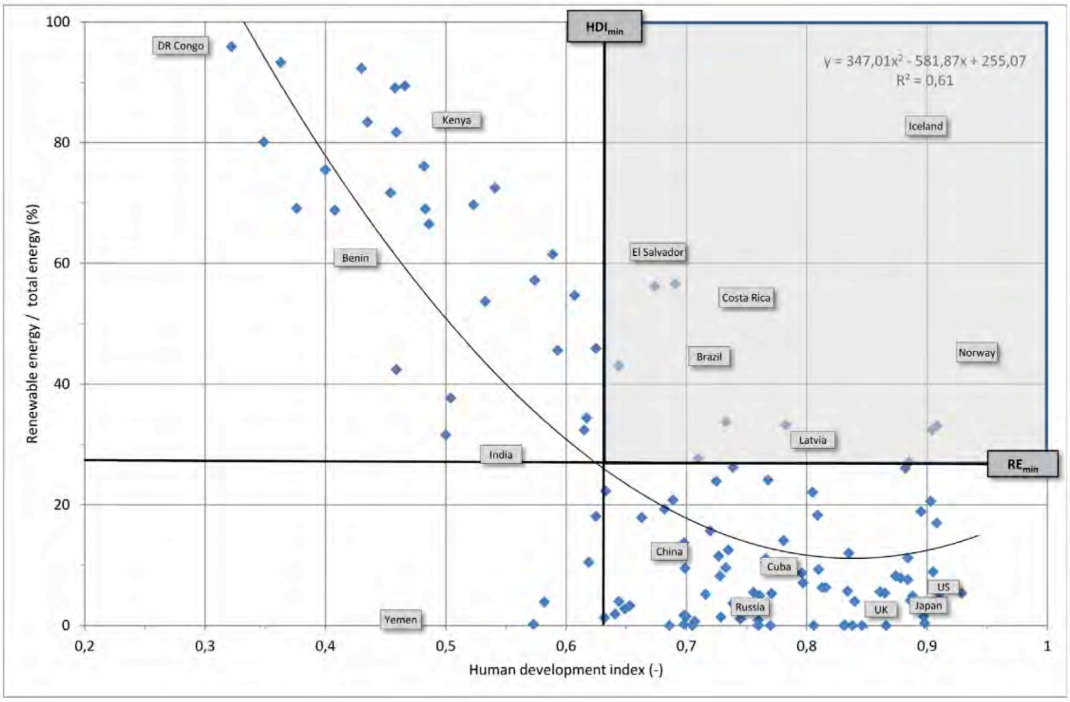

Figure 2: Relationship between Renewables and Human development index (Holden et al 2014)

Figure ones data shows that as the human development index rises, ecological footprints increase exponentially. Highlighting the demands on nature in providing for humanity, as more inhabitants are provided for, consumption levels increase, having a knock on effect within the economy increasing demand for resources further up due to increased prosperity for society as a whole. This from the data of the two primary dimensions it is evident that balancing the two is inherently difficult, but not impossible and it would require societies with an advanced human development index to seek means of reducing their demand on nature without sacrificing economic prosperity. Surely Renewables have a role to play then? Figure 2 shows that countries with high levels of renewable adoption, in fact, have lower human development indexes. Almost counterintuitive, however understandable in that the countries with the highest development indexes have prospered as a result of access to fossil fuels and the use of them. Expectations exist such as Norway, which has managed to achieve a high development index while using renewable predominantly proving that balancing the two is not impossible, just improbable due to global power struggles of the major consumers. From the above figures it is evident that not a single nation has yet managed to achieve all four primary sustainability parameters. You have to question why not? Are the sustainability goals socially acceptable and attainable, if yes, which one would presume then that society would drive the change, however this is evidently not occurring? The only logically explanation for this is due to the policies employed to drive the change and promote sustainability. Government believes that promoting economic growth will drive forward sustainability. However, while this may achieve targets, economic growth isn't a primary dimension of sustainability, another issue is that of acceptance and participation. The saying "the rich get richer" comes to mind, the richer also in turn require ever more consumption, in turn creating further benefit from this consumption while the "poor get poorer" this process satisfies some of the primary dimensions while ultimately driving sustainability further from reach. Solving this issue and balancing the primary dimensions of sustainability resulted in the progression of the following chapters from initially looking at the issue of the societal dilemma that is sustainability, and how relying on society alone with a centralized driver as is the current form will fail in the task, to seeing if structure and individual agents can solve this issue as an aggregation of individual self-interests. Ultimately the approach most desirable is the one, which will lead to acceptance and participation in aligning economic and ecology goals that a gap exists between our views towards them, is evidence enough that a new energy paradigm is required, getting there however proved complex.

2.2 Game Theory

"*Danny: You can be as morally righteous as you want—in a vacuum—but throw in a second entity and you gotta start acting in response to the other.*"

― Angry Zodd, *Danny the Last Earth Man*

Remember the dilemma of turning off the light bulb? Assuming man does not live in isolation, it would be safe to assume an awareness, that in the current climate of energy shortfalls and enhanced "awareness" of the need for sustainability, there exists a clear externality of failing to turn off the light bulb, manifesting itself in the form of an increasing energy demand in the face of consumption curtailment calls. Subconsciously as rational individuals, with access to knowledge of the current energy climate, there is knowledge of the need, and the consequences, of the action taken. A brief side on this "notion of knowledge" the degree of knowledge plays a surprisingly large role in everyday lives, which will be discussed more thoroughly later in the chapter, but for now simply common knowledge is not the same as mutual knowledge. "I know my neighbour knows of the need for consumption curtailment, but I don't explicitly know that he knows that I know" Thus assuming neighbours don't discuss global environmental issues, there exists only a mutual understanding of the need to turn off the light bulb and not a common knowledge understanding. Perhaps then in this climate of mutual understanding, when making a decision one neighbour looks out the window and notices that the aforementioned neighbour has the light bulb burning, a light bulb he views as being an unnecessary extravagance such as his burning, arguably is, in light of the reduction calls, nonetheless however, one which imbues on him a sense of increased comfort and perhaps a degree of self interest in the form of greed. Thus, now as a rational (this notion will be addressed further in following pages) individual, the neighbours choice of leaving the light bulb on (he has no reason to assume he will turn it off) left him no alternative but to favour the preference of leaving his on so as not to sacrifice his own individual comfort without the knowledge of a reciprocal action. This scenario is what Bateson referred to as a *Double Bind (*Bateson et al, 1956) (as a side note, among others he presented a credible argument for double bind induced schizophrenia).

Game theory in essence is an interactive decision making theory, representative of When an individual, or collection of individuals, possesses the ability to make a decision between two or more options, in order to maximize their utility, while simultaneously another individual or collection of individuals, makes the same decision between two or more options, with the decisions of one affecting the other. In his work titled *Leviathan,* which many regard as the founding work in modern political sciences, Hobbes (1651) states that *"Liberty, or freedom, signified properly the absence of opposition (by opposition, I mean external impediments of motion); and may be applied no less to irrational and inanimate creatures than to rational"* (Hobbes, 1651 par 21.1) in essences he states that the best situation for all individuals is one in which they exist to do as they please. He counteracted any potential tricky issues such as that of anarchy, by proposing temperance through, the collective appointing an agent with the ability to "punish" those that selfishly act within their own interest against the interest of others. The world has changed a lot since he penned that in 1651, the common does not seem as "infinite" anymore, in a game of bargaining, the issue of the commons is arguably that of a trade-off between outcomes, freedom to act often becomes freedom to concede to another's demands. The following discussion on game theory will highlight the way this individual and collective freedom alters the decision-making process in a societal setting, which as a consequence has an impact on our socio economic and socio technical systems we are inked to. Paving the way for the following chapters where this desired, and protected, freedom is moulded for the benefit of not just the collective but that of the individual through mechanism design with the intended aim of solving the social game that Is sustainability.

2.2.1 Playing the game: The basic elements

Current Sustainability policies require the collective needs being held above the needs of the individual instead of the collective outcomes being governed by the individual's needs and actions. This relationship is an example of a social dilemma, created through the conflicting nature of interests involved as a result of social interaction in a centralized system. Socially interactive relationships are not governed by pricing mechanism related to energy at the time. This reliance on the intrinsic altruistic nature of the individual to drive sustainability is inherently flawed when compared to the dominant extrinsic neoclassical means of attempting to achieve energy sustainability and quantify the outcomes. Neoclassical economics is driven by the assumption that Humans are intrinsically self-interested as exhibited by rational choice theory, while they do not actively seek to harm others or in that they do not have an overriding level of conceitedness leading to care of themselves above others. They do, however, have a unique sense of what the preferred state of order is; hence this self-interest governs actions and opinions as well as how they account for these actions and opinions. This extends into game theory, as this self-interest has an effect on the possible outcomes available to the spatially connected players through the creation of competition amongst the individuals or, coalitions, for utility maximisation.

Competition alters a player's mind-set as to the preferred possible outcome based on their level of rationality and their quest for strategic dominance. In social interaction, such as the call for sustainability, rationality becomes self-defeating in that it requires irrationality to optimally succeed contradictory to the strict notions of rationality, which govern the models. Rational thought means that the individual will seek to maximize strategic dominance based on their perceived utility. This Rationality implies that even though cooperation imbues greater reward, the lack of common information regarding the other players in the game, means that the rational choice would be to take the option of lower rewards but greater security of outcome for self. This hints at the failure of the structure of the supply model in relation to sustainability calls where success hinges on rational players acting according to how they individually perceive other individuals to act in benefiting themselves, without having the common knowledge that all players are rational. With its roots in economics, game theory implicitly understood that understanding perfectly competitive markets or monopolies are reliant on parametric analysis. Rendering it markedly difficult in applying models to circumstances where non-parametric aspects hold relevancy. With game theory their now existed a means to logically justify, and to an extent, quantify, actions in rational terms, along with the view that actions must often be justified in line with their expected outcomes. Applying this "new theory" relies on an understanding of certain elements within the notion of game, what is utility and preference? How do I define rationality? What exactly is common knowledge? Here these notions will be discussed mainly due to their relevancy in this chapter in analysing societal freedom and for the paper in general in creating an understanding on why society ignores obvious patterns of failure.

2.2.2 Agent Utility

Mans Everyday actions have an effect on the economy of which all are an active component of, through consumption and production, individuals become economic agents. By definition an economic agent is an entity with preferences, these preferences are describe through the concept of *utility.* Utility is however fundamentally a subjective notion, representative of the tendency of an object or action to cause an increase or decrease in mans overall happiness, or derived welfare, which he references against an individual background framework. This notion of utility is directly seen as a rule of rationality and in particular rational choice theory (to be discussed in 4.1.2), which substantively holds the view that people should seek that, which maximises their utility. Utilities subjective nature is due to the internal frame of reference, or what is more commonly referred to as psychological fulfilment, which renders it as a consequence, difficult to quantify, creating an inconvenience when modelling. Consumption economists realised this subjective shortcoming when facing issues of decreasing marginal demand and utility. Their solution was through Paul Samuleson (1938) who successfully altered the concept of utility from subjective to technical.

Utility, thus, when applied to a pure agent holds the same subjective nature of welfare; however, when applied to an economic agent that agent now seeks, instead, to maximise a utility function, not pure subjective welfare. The Utility function is the relationship between consumer preferences and market conditions, or generally the relationship between goods, prices and agent income. The notion of utility has different implications when applied to agents acting under certainty or uncertainty constraints within the energy grid. This concept of utility and an agent’s utility function are vitally important to the principles of game theory and in its associated sub form of mechanism design which is the subject of discussion in chapter five. But why does utility change under uncertainty? The answer lies in the subjective nature of our internal reference points and the effects external triggers have on it. Game theory proved that while individuals are rational agents, individuals are none the less subject to constraints and those are never more evident than when they are faced with fading certainty.

2.2.3 Utility under assumed Certainty

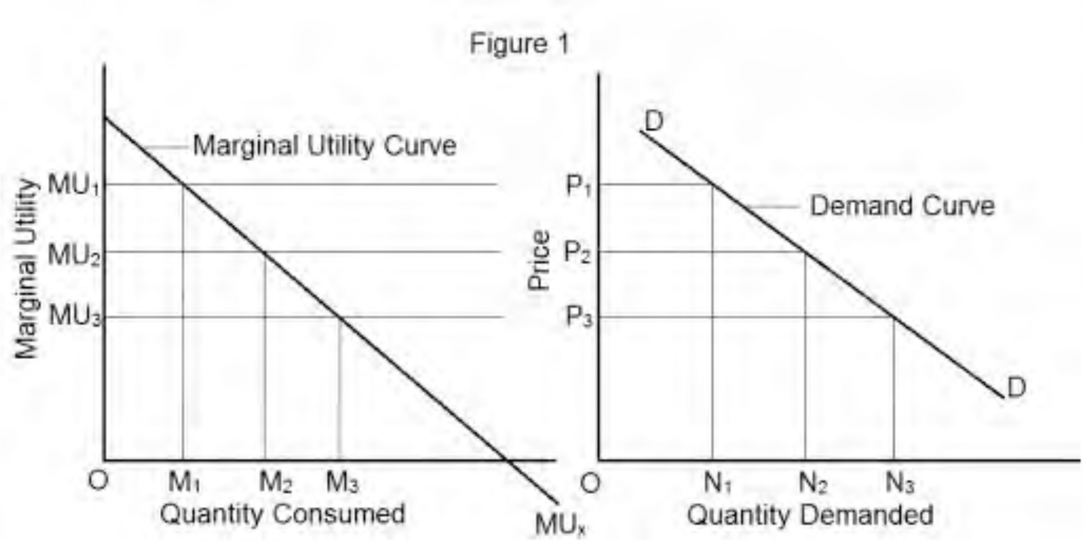

Figure 3: Typical demand curves (Hubpages, 2015)

Neoclassical thought relies on the link between prices, demand, quantity and utility to assess the state of the current energy climate and its effect on an economic agent who by typical models is a consumer in an environment of assumed certainty. This certainty assumption is attributable to the existence of a perfectly competitive energy market due to the inability of an individual economic agent to significantly alter the price of goods or services (Sanstad, 1994). Arguably the current supply monopoly has the ability to alter prices; however, that alteration affects all and as such applies to the definition of a competitive market in the classical sense. Energy is arguably not consumed directly by individuals, consumption occurs as result of demand derived from the flow of services from energy consuming appliances. Consumption occurs on an aggregate scale over time, while demand is occasion specific. This is an important characteristic of energy use; demand plays an important role in the development of a competitive energy market.

These demand characteristics have two distinct components in terms of short run and long run demand elasticity's. Long run demand elasticises are relatable to consumption reduction over time due to the adoption of energy efficient measures or renewable production, while short run demand elasticity is more indicative of behavioural changes. In consumer theory, price is related to demand and supply with the law of demand stating that an increase in price will lead to a decrease in demand. This, in theory, implies that in the classical model under presumed certainty and with a linear pricing structure, it in fact would not be effective at reducing short run demand, only altering long run consumption. But how does the cost of energy affect utility and how that utility is quantifiable or observable, specifically in relation to short run and long run demand elasticity scenarios. There are two ways of understanding this issue (1) That of static utility function where an individual optimally allocates resources, generally in the form of income, to achieve maximum utility. (2) That of the extended static form of dynamic utility function or inter-temporal utility, which includes the dimension of time and weighs future utility against current utility. As discussed earlier, consumption and demand are as a result of an energy service, in effect individuals “produce” their own service through various inputs (energy supply) with various energy consuming technologies. Hence these services and goods are inputs to utility. (Sanstad, 1994) With this in mind the basic static version would imply utility is derived through an increase in service or a decrease in input within the confines of an income constraint. Static utility maximisation relies on an individual maximizing their budget constraint (income level) by allocation more to what they derive greatest utility from, utility levels increase, however, after a certain point the utility derived from an action increases slower and thus marginal utility is evident.

This notion is inconsistent and basic when applied to energy use, in that the utility derived from energy use is an aggregation of utility over a period of time in real-life scenarios with utility derived from the energy services as a function of the energy input. Dynamic utility has great applicability to actual real world models in that allows for the budget constraint to be bypassed as evident in everyday life. Individuals have a preference for current consumption over future consumption leading to a discounted utility maximisation due to characteristically weighting future utility less than current utility (Sanstad, 1994). There is however still the overriding problem with this view in its assumption again of perfect information and certainty, due to the assumption of a fixed monetary discount rate which ignores the marginal cost of money. When applied to a scenario with implicit risk, assuming the future value of money to create certainty creates a large issue when gauging the future expected utility, as is the case in energy investment, ignoring the assumption creates uncertainty, which, as individual agents will be proven to be inept at handling. Mathematically representing this binary relation between preferences and certainty is straightforward and helps define what a rational decision is. X (finite set of outcomes) with x, y, z (common elements), x represents x being weakly preferable to y and representing x being Strongly preferable to y. The preference relation can be defined as rational if it is complete and transitive. Completeness is defined as an individual having an ability to determine a clear preference between two outcomes. I.e. x, or y, with x y. Transitive implies that pairwise choices cannot form a cycle I.e. if x y and y then x. This definition of rationality helps model what a rational decision between outcomes is, however it is severely lacking in applicability to real world scenarios in that it does not factor in the consequences of uncertainty created by various variations in the nature of individuals and of the society in which we are a component of.

2.2.4 Utility under uncertainty

The above brief description of Ordinal and cardinal utility functions under assumed conditions of certainty dealt with the basic notion of preferences between two alternatives or outcomes for an individual in a pure market, and helped mould the notion of rationality in an agent. But what of the situations when the consequence of a decision and not the preference between outcomes becomes more relevant and is based on the undetermined actions of another individual who is spatially connected? In these cases, certainty cannot be assumed, such as is the case when making a financial based energy investment with payback periods in the future (arguably even a time or effort based investment could ignore the assumption of certainty, however generally a financial decision holds greatest uncertainty in that it is quantifiable in a relatable medium). Often when making decision, an individual has to be certain of the consequences of that choice. A decision with uncertain outcomes has the characteristic of the probability of the outcome defining the risk. An important concept within game theory is the von Neumann-Morgenstern Expected Utility Theory (*vNM*), which models uncertain prospects as probability distributions over outcomes. Its main limitation is that it deals with uncertainty as an objective risk. As a theory, *vNM* is a normative tool to deal with rationality and decision-making at the level of the individual. However, it often fails in accurately predicting individual's actions, mainly due to the fact that individuals do not act as expected, in particular with the stringent requirements to be defined as rational agents. This is evident in proofs such as the Allais Paradox, and was evident in the case study later. Thus here, it is used to form a basis for how people should act, but failing to account for deviations from base assumption. Formally, thus, expected utility is based on the weak ordering principle in the form of completeness, transitivity and context free ordering or colloquial, continuity in preference between options. The overriding theme of game theory is the notion of agent rationality and the pursuit of utility. But what exactly does rationality imply? And what consequences does the notion have when modelling a social dilemma?

2.2.5 Rationality in social interactions, or the limits of

Game theory attempts to understand situations where decision makers interact, sustainability as an inherently social problem is representative of this scenario, but what exactly does being rational mean? Manktelow and Over (1993) simply stated that rationality involves behaving and thinking reasonably and logically as well as knowing that others in the same system or game are also rational and will act to maximize their individual circumstances, in several forms, namely: (1) Rational beliefs which are internally consistent (2) Rational arguments are those which follow the rules of logic and for this discussion (3) Rational preferences and (4) rational decisions which require a lot more thorough explanation and understanding. However, perhaps a good point to start with is the understanding of what rational choice theory assumes about human psychology. Shepsle (1995) viewed rational choice as a particular bad scientific paradigm, while cox (1999) views it in the more accepted game theoretic sense as a form of a methodology. Rational choice theory holds the view, or assumption, that complex social phenomenon can be explained through the elementary individual agents which it consists of. In essence, the aggregate behaviour of society is a sum of the individual choices of the agents. Elster (1989) eloquently explained social institutions as the notion that *the elementary unit of social life is the individual human action.*

Thus, the first note on rational choice theory is that: (1) it adopts a methodological individualist position in its attempts to explain societal phenomenon in terms of the rational calculations of self-interested individual agents. A second note on rational choice theory is how it perceives social interaction (2) Social interaction is social exchange, individuals are explicitly motivated by the potential reward, or threatened by potential consequences, each having an effect on the expected utility of an action. Modern views on rationality are a normative based model of the idealized individual decision maker, focused not on the description of real people (Tversky and Kahneman, 1989) but instead on the how of action. This normative approach to modelling decisions through the logical analysis of decision making under uncertainty, is defended (rather weakly) by subjective views such as Schumpeter (1954) claim that it is "has a much better claim to be a logic of choice than a psychology of value" or the more rational argument for a normative approach is the understanding that individuals are generally effective at pursuing their goals, especially under a cloud of incentive or learning possibilities. Focusing not on the descriptive (subject for part II) but on the normative analysis of the how assumes certain characteristics of decision making in order to render an individual rational within the constraints of the model. These assumptions are rather broad in their applications. For example the invariance axiom for rationality states that *preference between options should be independent of their description*, Tversky and Kahneman (1989) refer to this in their descriptive Prospect Theory as the framing effect (which unlike, RCT, they view as actually having an effect).

This implies that a rational individuals' preference is constant regardless of how the options are presented to them, this is justified by the logical representation that variations in the form of description have no effect on the end outcome. Logically (if one is purely rational) this notion makes sense, however according to the stringent requirements of rationality in game theory and RCT falling victim to the framing effect would render you irrational. Another critical assumption in normative rationality is the dominance axiom *If option A is better than option B in one state and as least as good as B in another, then A is the dominate option.* Simply put, to be rational, an individual must be constant in their decision and preferences, a normative essential, which renders a descriptive analysis invalid. Clearly the rationality requirements for a normative model are stringent and arguably lacking (argued in Part II) however they have a role in describing how an agent should act if they wish to maximize their utility. This provides a platform for modelling ideal societal actions as well as providing a stepping-stone to deeper, more descriptive analysis incorporating behavioural traits later.

2.2.6The role of logic: Knowledge assumptions

"We believe that human beings cannot gather information without in some way simultaneously developing alternatives. They cannot avoid evaluating these alternatives immediately, and in doing this they are forced to a decision. This is a package of operations and the succession of these packages over time constitutes the total decision making process." (Witte 1972, p. 180.)

The concept of knowledge and in particular that of common knowledge is central to an explanation of collective action and cooperation. Our collective action is dependent on us having appropriate expectations and understandings about each other's behaviour. The formation of these expectations is only possible if common knowledge exists, and as such is a crucial assumption (alongside rationality and game structure) in game theory, and in general cooperative normative social models. There are various levels of knowledge or interactive knowledge, but the two simplest cases are: (1) Mutual knowledge: being a first order level knowledge, where external state knowledge is gained in the absence of interactive knowledge, or *if all players know fact A*. This idea might seem simple, however, simply having all players knowing information does not imply that common knowledge exists. This assumption does not clearly identify what players think other players know. Hence *(2)* Common Knowledge: is a higher order knowledge, our knowledge about the external state is shaped in the presence of interactive knowledge, or *if all players know fact A, and we all know that everyone else knows A and we all know that everyone else knows that everyone else knows A etc. etc*.

This infinite, or hierarchal, view was developed by David Lewis (1969) and in it he understood the limitation that a finite agent is able to entertain the infinite amount of states required in order for common knowledge to form. He solved this issue by refining the notion of common knowledge into actual belief and reason to believe, and thus he preferred liking common knowledge to "reason to believe" over a tangible fact. However, Human knowledge when modelled does not behave such as computers do in that computers knowledge has its basis in mathematical logic whereas humans is based on probabilities and set theories. In probability theory and by extension game theory, information is represented by an outcome or "*possible states of the world*" and the probability to achieve it based on the level of knowledge amongst the players. Enhancing this knowledge leads to higher probability of success through an associated reduction in risk. This is in contrast to the subject of Part II, Decision theory, which focuses instead on the individual and how we use our freedom, while operating under uncertainty. The lack of formalization of Lewis's common knowledge was more formally represented by Aumman's representation of common knowledge who's framework allows for the direct formalization of Lewis's intuitive notion of common knowledge in the form of probability of an event occurring (vs. knowledge that each knows the event) with beliefs based on prior uncertainty for an infinite uncertainty space. So with common knowledge still having a basis in individual belief, what use is common knowledge then in the idealised sense of game theoretic models? Arguably the answer lies in the notion of conventions and the understanding that agents have common knowledge of the conventions to which they are parties. These norms by which we base our daily lives and action on are linked to our behaviour and the attached consequences of those actions. David Lewis (1969) believes that these conventions lay at the core of games of coordination, introducing the idea that in order to have reason enough to chose a particular action, the agent needs a high enough degree of belief that other agents will choose a particular action. These social conventions he believed are sustained by common knowledge, highlighting the role common knowledge plays, not just in our actions but also in our beliefs.

2.2.7 Mathematically representing the ills of society: The N-person prisoners dilemma

Game theory being an interactive decision theory understands that collective action plays a role in creating a unique social dilemma when it comes to resource allocation and its use moulded and governed by the competitive environment which is promoted in modern society as the means for attaining all that is desired in life. A social dilemma has two characteristics: (1) Individual social payoff is higher for defecting behaviour, in all cases, regardless of the actions of other individuals (2) All individuals receive a lower payoff if all defect vs. if all cooperate (Felkins, 2011). The tragedy of the commons is a social dilemma, one a bit more different in structure to that of a Prisoner Dilemma game, however consistent with the notions of it. Raimo Tuomela (1992) eloquently states that "*The problem of collective action can then be taken in a preliminary way to be a dilemma or conflict between collectively and individually best action, where the action required for achieving the collectively best outcome or goal is different from (and in conflict with) the action required for achieving the individually best outcomes*". The use of the PD in the case of a social dilemma is of the iterated extensive form, and not that of 'Tit-for –tat' those strategic versions where decisions are made concurrently and with reciprocated linear payoffs. Often we make our decisions based on past experiences and knowledge thus understanding social dilemmas is important in that they represent and illustrate the conflict of motives and highlight the limitations and practicalities of the structure of the institutions, which govern society. Why do some communities or organizations cooperate more then others? One view (which will be critically analysed and argued against throughout and in this section) is the current top down hierarchical model of energy supply, where the government coordinates and regulates individual behaviour into conforming to requirements of the function system at a level of aggregation, which is higher, than that of the individual. Central authorities back this by enforcing policies and regulations and are aided by individuals who are socialized to conform by cultural norms produced by societal interactions. This characteristic is often refereed to as “our “ race to the bottom and the *N person prisoner’s dilemma* can be interpreted as the mathematical representation of *what is wrong with human society*.

2.2.8 Playing the game

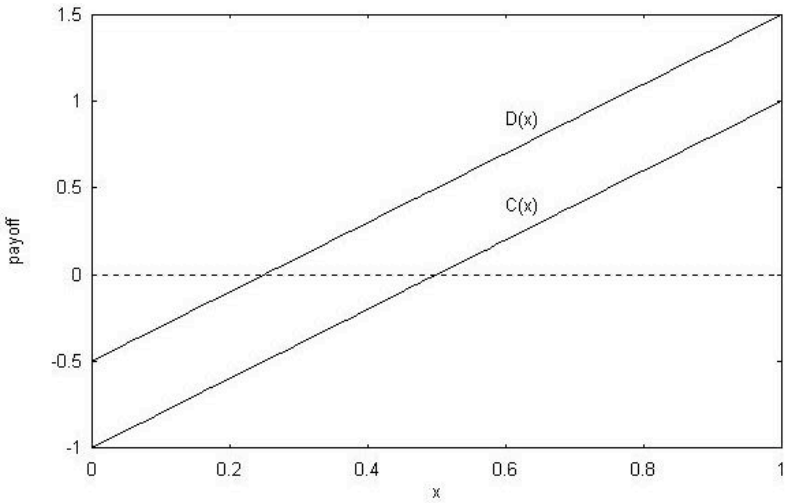

Figure 4: Payoff (utility) vs. percentage of co-operators (x) function. (Szilagyi, 2003)

In the *N person prisoner’s dilemma* (NPD), each participant, participant being an individual, collective of individuals or organisations, also referred to as an *agent* (will be discussed in chapter five) have a choice of two actions. *Cooperation*, C (x), with the collective for the common good, or *defection*, D (x), in favour of self-interested short-term objectives. Each individual receives a payoff in the form of reward or punishment for each action that is not only dependent on their own actions but everyone else’s actions. From game theoretic assumptions and mathematical modelling the above graph was found to represent how individuals should/will approach a game (or in this case sustainability) it is evident that there are two distinct mathematical conclusions form the graph, which formulate the dilemma.

1. D (m) C (m+1) with m being the number of participants (N) cooperating

2. C (N) D (0)

This graph however is a limited representation of what a real world setting truly is and understanding the intricacies and fundamentals of a fully encompassing game is beyond the scope of this paper. Not due to the mathematics involved, but purely down to the computation power required to compute an infinite amount of variations due to the infinite amount of varying payoff curves between individuals and that is for a uniform game, not a game with non-linear payoff curves. There is no general universal NPD; this Luckily is resolved because the N-person game is a compound game, reducible to a series of two person games if both payoff functions are linear. Hence a dyadic version of the game is a limited subset of the full N-persons. When modelling the game in its entirety, it is necessary to make assumptions of the environment and of the agents who occupy it in order to make modelling more manageable. Assuming a uniform and iterated game, where agents are distributed fully and occupy a finite space, where agents lack knowledge of others actions and for simplicity sake who's actions are simultaneous, how then do payoff curves and personalities effect cooperation in achieving sustainability? Using the model generated by Miklos Szilagyi (2003) it becomes clear that the effects are negative.

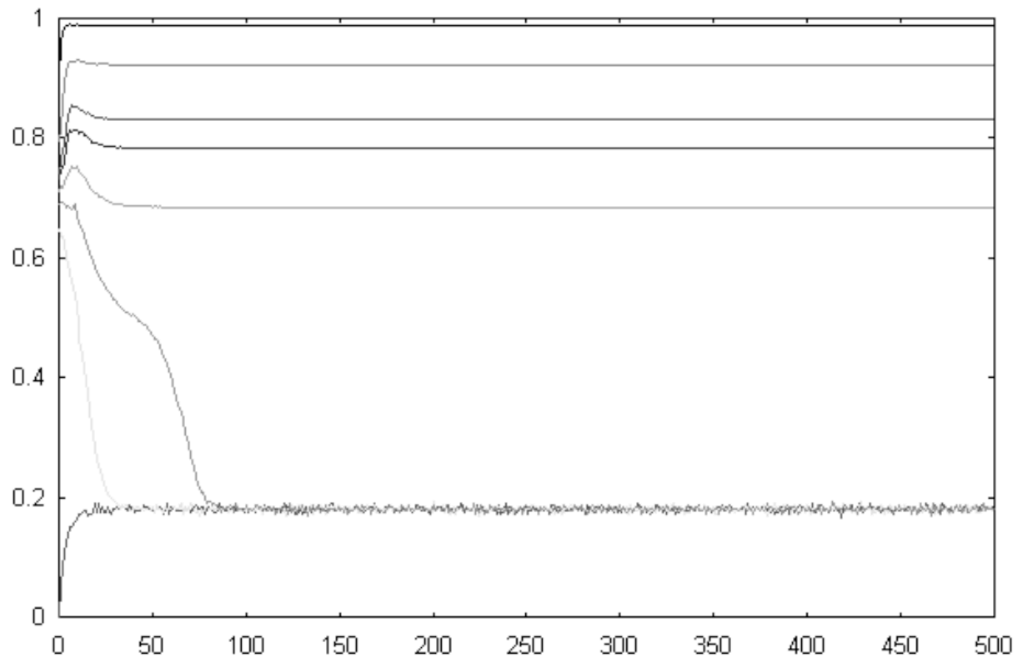

Figure 5: Proportion of cooperating agents as a function of the number of iterations for pavlovian agents (Szilagyi 2003)

Figure 5 is a simulation from the model of the entire collective of agents, assuming various initial levels of cooperation, the first curves is 0.9, the second 0.8. Then: 0.75, 0.73, 0.71, 0.69, 0.65 and finally, 0.00. The agents are deemed Pavlovian, in that there response to other agents' actions are stochastic, but their probability of cooperation *p* changes proportionally to the payoff from the environment, either in the form of punishment or reward. The agents are deemed primitive enough to not know about their rational choices but intelligent enough to learn behaviour in line with the law of effect, in that behaviour followed by a pleasant consequence is more likely to be repeated then a behaviour followed by an unpleasant consequence.

From figure 3 with linear payoff curves $x\ C\ (x) = (1 - x)\ D\ (x)$, with the ratio of co-operators $x = m/N$ and the ratio of defectors is $(1 - x)$ at a point in time on the graph. This linear payoff leads to equilibrium, one stable and the other unstable due to the function being quadratic

1. If C (x) and D (x) are both negative, it implies that a small number of co-operators are punished severely and a large number of defectors are punished slightly. This tends towards a stable equilibrium with = 0.180

2. If C (x) and D (x) are both positive, it implies that a large number of cooperative agents are rewarded slightly while reciprocally a small number of defectors are rewarded greatly. This tends towards an unstable equilibrium with = 0.695.

From the simulations they found that when the initial ratio of cooperative agents was below then the solution of the game tends towards in the form of an oscillation. In the case where the initial cooperation ratio was above the curves tended towards and stabilized. In no case did the curves reach a convergence in the form of a proportionality of 1, i.e. Full cooperation. This is due to the notion that an agent who started as a defector will more then likely tend to stay a defector in the long run due to the better payoffs. The results differ slightly when a layer is applied to the simulation and the agents are arranged in a community with a smaller number of agents.

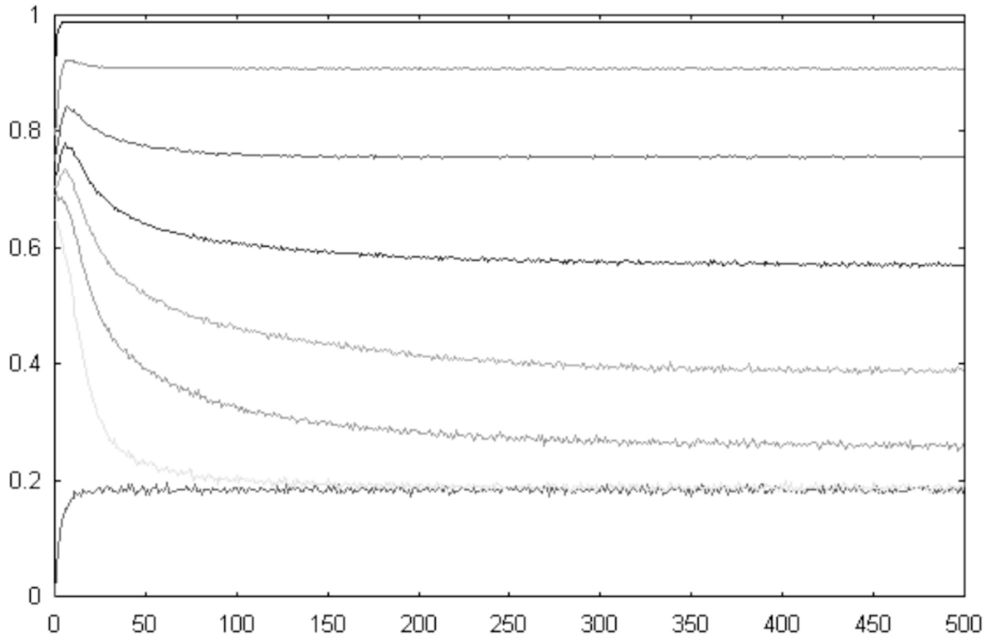

Figure 6: Proportion of co-operators as a function of iterations over time for pavlovian agents in a neighbourhood one layer deep (szilgayi 2003)

In this case neighbouring agent's behaviour influences the payoff resulting in a more gradual dependence on initial convergence ratio. With lower ratios of cooperative agents, as a result of the influencing behaviours, Figure 5 and 6 simulate the final aggregate outcome for cooperation at the level of society and a smaller neighbourly level both simulations prove that in the case of a linear payoff curve and low initial cooperation levels, the equilibrium cooperation rate will not exceed 50% (Szilagyi, 2003). It is natural to note that the results heavily depend on the initial payoff curves, while this is a simpler representation of non linear cases, it also highlight the role the payoff curve plays in the game and perhaps is the reason why cooperation levels can never exceed 50%. The reason I believe (and partly prove in the case study of chapter seven) is attributable to the discrepancies between competitive and cooperative process in society.

2.2.9 " …you gotta start acting in response to the other" The limits of competitive processes.

Darwin understood that individuals compete for scare resources, understanding that if all individuals must compete and all individuals vary, then over time those with the dominant variations will have greater opportunities at progressing to subsequent generations. The key idea here is the notion of competition, we live in a world, which requires cooperation to avert the issue of the commons, but society advocates competition ("*competition brings out the best*") as a means to advance in society.

This competitive cycle creates a loop where those who are "strongest" in this case those who use more, proliferate and create a feedback loop that results in increasing consumption and harm in future generations, as Darwin predicted that competition aids evolution through these dominant variations proliferation. This creates not just the issue of over consumption in favour of utility maximisation, but of greater potential for defecting in the sustainability game. In the NPD competitive markets were "proven", and the word proven is used lightly because there is no clear definition of what constitutes a real life setting, to show fundamental limits in achieving optimum long term iterated strategies or outcomes. Wright (2001) made the case that *"competition is best if resources are scarce, cooperation if resources are abundant"* but a resource is not just natural, expanding computational abilities and access to information is an abundant resource, which has the ability to enhance and tip the favour from competitive process to cooperation.

This abundant resource helps show the systematic patterns of failure are consistent in their characteristics, which is now apparent to see. There will always be a level of competition, even if cooperation is optimal; being system sensitive after all, there now exists need to understand the trade-offs and manage the consequences of it. Competition affects an agent's intrinsic and extrinsic motivation; competition can only turn an intrinsically motivated individual to that of an extrinsically motivated one. Moving them from engaging in an activity (cooperation or defection) for its own sake to engaging in the activity based on incentives external to the activity. This manifests itself in short term gains in spite of long-term losses if cooperation were evident. Kohn (1993) went so far as to prove experimentally that extrinsic motivation is successful in the short term; however, in the long term it leads to decreasing levels of intrinsic motivation. In essence, in the long term individuals become more competitive and less likely to cooperate. Perhaps the overriding outcome of this chapter is the importance of education and information. Educating society on the limits of competition aids the potential for the emergence of cooperation, which will promote intrinsic motivation and the ideals of cooperation in achieving sustainability. Unfortunately the current system is lacking in its ability to describe the dynamics by which society moves from one equilibrium to another in relation to our forward thinking rationality in part due to the lack of information and partly due to system and internal constraints, far from the epistemological notion that we are not only interested in our knowledge but also the knowledge of other individual's knowledge base.

Andrew Colman (2003) asked the questions, *is rational social interaction possible?* Freud (1911) argued that rational social interaction relies on the distinction between his two principles of mental functioning, which of the two, the reality principle and pleasure principle, the reality principle is the one which only posses the ability at being termed rational. Game theory relies on this rationality, ignoring the effects of irrational thought, thus rational social interaction is not possible if individuals are viewed as ideal agents in a centrally controlled hierarchal system with only partial control of outcomes, as rationality is more applicable to individual decision making and does not transfer as well to interactive decision making. However, if that system is instead structured so as to create greater control of outcomes for individuals while internalising, or at least compartmentalising, consequences, perhaps then it could be possible. Clearly there exists a need to align the notions of structure and agency.

2.3 Mechanism design in resource allocation

A bad system will beat a good person every time.

- *W. Edwards Deming*

If chapter four was the socio-economic dimension of sustainability, arguing that society is responsible for mans race to the bottom, how exactly then is sustainability achieved, when it is impossible to avert the creation of a social dilemma and detach energy use and its effects from its primal role in society? The solution potentially lays within the concept of Mechanism design, which believes that the answer still resides within the individuals of society, but its focus is reliant on interventions and policies directed at resource allocation, inline with how individual agents are viewed, and then structure their potential actions within the system, furthering the ideas formed in traditional game theory. In essence, it is the art of designing a game among strategic agents so that a social goal is realized. While similar in principle to that of game theory, there are however clear divergences on the how individual agents are perceived in their role within a centralised or decentralised system structure.

Unlike in game theory, mechanism design, rather than investigate a given strategic interaction, starts with certain desired behaviours on the part of agents and focus instead on what strategic interaction among these agents might give rise to these desired behaviours. (Yoav and Leyton-Brown, 2009). Understanding implicitly that the institutional design within which individuals interact has a profound impact on the result of the interactions themselves, this I will show to be true in theory, and later on in the case study which highlights the notion that the primacy of agency, which is often touted as the solution can not in fact be segmented from its reliance on structure to limit and influence behaviour so as to avert anarchy and system collapse through total freewill. This does not imply that I view totalitarian control the answer, merely that how we form the institutional structure is important in directing individual’s actions to that of sustainability, particularly the actions of those willing or capable of enacting change.

Previous chapters showed that relaying on the rational actions of the individuals of society; in what is ultimately a competitive environment for decreasing resources will cause sustainability to fail. In this chapter, instead, will focus on how to structure the energy institution so as to promote and enhance, sustainability objectives and achieve a common goal for the collective which may not be that common to individuals but aggregates itself in maximum utility for all. Firstly looking at the indivisible component of the system, the agent, through a better understanding of the potential inherent within an agent based approach it is then the apparent role of the structure to direct those agents' actions. Deciding on a centralised, or decentralised system is not always clear-cut and aligning the characteristics of each is important in facilitating an improved institutional setting for energy use and the diffusion of society's replacement of natural resources in the form of the technology solution. Arguably replacing natural resources with man made resources goes against the views of ecological modernist views towards sustainability, however the man made resource that is information can hold the key to protecting intergenerational natural resources, this notion will be discussed in this chapter and referenced in the case study later in the dissertation. If the rational actions of man are sustainability's downfall, perhaps structuring the potential actions to achieve an outcome is the rational solution.

2.3.1 Why is there a need to start allocating resources?

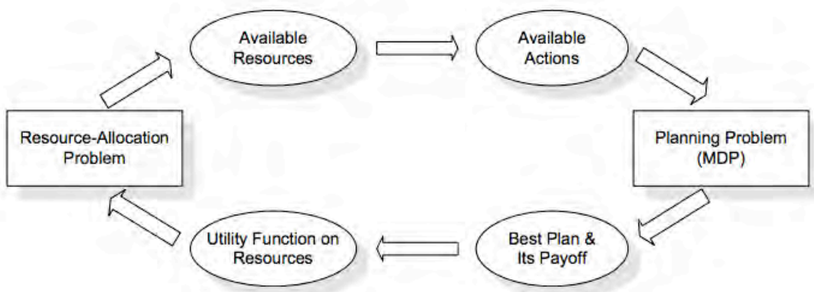

Figure 7: Dependency cycle (Dolgov and Durfee 2006)

Sustainability in essence is a form of virtuous management, managing the finite today so that future generations have access to them. Resource allocation is key to that; in this case resource allocation will centre on that of the fundamental energy resource. The over riding question in resource allocation is how to distribute a set of scarce resources among a set of agents, who can either be cooperative or selfish, which maximises global utility and perhaps more importantly social welfare (Dolgov and Durfee, 2006). In Figure 7 it is highlighted the main issue involved with resource allocation in the form of the dependency cycle. Utility is defined as in the previous chapter, as such in resource allocation; the agent's utility function is defined as a solution to a planning problem. Simple enough but in order to formulate the planning problem the agent needs to first know the resources obtained, which in turn depends on the planning problem of resource allocation itself, leading to a cyclic unsolvable situation in a closed loop.

Herein lies the fundamental problem of resource allocation; it is interdependently linked to a reliance on stochastic planning, which the current energy supply system is ill, equipped to parameterise a viable solution. Partly due to lack of accurate information and partly due to the complex nature of associated affects of efficient resource allocation, which are both positive and negative, with a need for balance between the outcomes and consequences. At the end of the day the simple fact (supported by the laws of physics) states that energy is required to perform almost every daily task, simply being more energy efficient is not good enough if we are only reliant on a finite set of energy resources, purely for the fact that when those resources have been exhausted, being energy efficient cannot replace the missing energy input that is still required, we would have committed “energy suicide”. Every industrialised nation has been founded on the backs of readily available access to cheap energy. America shines as an example, but managing the natural and integrating renewables means that de facto state wont be disrupted as long as mechanisms are put in place that dictates how society benefits from their individual portions of the common. Particularly of interest is how resource allocation is linked to the following three areas: (1) The unavoidable Economic development goals (2) The sufficient condition of social welfare and (3) The cyclic role of an increasing rate of Technology Diffusion. Understanding these three areas will highlight just how important resource allocation is as well as the critical role mechanisms play in facilitating the evolution of these systems in achieving sustainability in the long term.

2.3.2 Centralised and decentralised hybrid systems

In a socialist economy, decision-making authority is inherently vested in a central planner, who base their decisions on information communicated by individual’s agents in the system (Mookherjee, 2005). This is a contrasting notion to that of Adam Smiths recognition that information relevant to efficient resource allocation is, in fact, dispersed throughout agents in an economy, this contrasting form, to that of a socialist economy, in the structure of a decentralised market economy divests decision making authority amongst individual agents, who are motivated by their self interest and are coordinated by market prices. But which approach is optimal? Can decentralised mechanisms be replicated by centralised mechanisms? Leonid Hurwicz introduced the idea of mechanisms in 1960. He defined a mechanism as: *“A communication system in which participants send messages to each other and perhaps to a message centre and a pre-specified rule assigns an outcome (such as allocation of goods and payments to be made) for every collection of received messages”* (Hurwicz 1960). This definition of a mechanism highlights a few key areas of concern, namely what is the cost of the information requirement and how does one counteract weakness in a system with distributed control, both areas are central to the debate between advocacies of either system structure. Perhaps though the solution lies in a hybrid approach, which harnesses the power inherent in, the information held within the collective while vesting authority in a central control authority with the ability to utilise this increased information potential.

A consequence, or perhaps a characteristic of decentralised systems is the creation of self-interested agents through the delegation of authority, which enables individual self-interest to be held above those of the collective, whilst still under the control of the centralised authority. This has two antagonistic dimensions, which in the debate between opposing camps have a need to be balanced, namely: (1) The incentive cost in controlling this delegation of authority, (2) The Communication cost and distribution information processing responsibility (Mookherjee, 2005). In essence, the incentive costs needs to be held against the communication and information benefits and abstracted in line with the principle virtue of a centralised authority that is the control, for the benefit of the collective. Some would argue that the incentive properties of decentralised systems could be replicated by well-designed centralised mechanisms. But is delegation of authority optimal in resource allocation? With that virtue in mind, how does a control authority make resource allocation socially optimal? In other words, is it possible to use individual notions of utility and reported values of a common resource to enhance the collective standing, without concurrently adversely effecting individual utility functions? It is possible to use a centralised control authority, as long as a suitable mechanism is employed which will guide their actions to enhance the collective wellbeing. Employing a Vickrey-Clark-Groves mechanism (section 5.2.1) within this system will enable efficient resource allocation, the maximisation of social welfare and the potentially increased adoption of renewable technology. However, employing a centralised system with a mechanism replicating decentralised principles, does came at the risk of an abuse of authority or failure on the part of the centralised authority. For this chapter, the focus will be on using the central authority to employ a mechanism able to protect the security of supply interests of society, however, chapter six will contrastingly try to show that perhaps a hybrid approach is optimal in the long run to ensure efficient resource allocation and increased security of supply whilst enhancing a decentralised approach to the generation of energy.

2.3.3 Public good vs. Private Good

Which is more important, security, or the simple supply of energy? Answering that question relies heavily on deciding weather energy is, or is not, a public good. Christopher A. Simon (2006) contends that the current debates on energy and the proliferation of policies are fundamentally a debate on the nature of energy as a good; In essence, is it correct to perceive energy in the form of a public or that of a private good. In a classical market setting, the nature of goods is important, taking either the form of rivalry or excludability. Simply for a good with rivalry characteristics, some individual's win and some lose. For example, some get the good and other potentially do not. However, excludability fundamentally refers to the nature of the good: i.e. are individuals able to simultaneously enjoy the good if another is using it without being excluded. A private good has both dimensions, a public good is neither, and is at the heart of an individual's existence in society and basic human rights. In a socialist society with an economic objective of maximising the societal benefits and increasing social welfare, which classification is the ideal? And does this contrast with the actual practical observed nature of energy as a good? In terms of energy supply security or fundamentally the quality of supply; in the current centralised grid systems, it is only possible to have energy as a public good in that if there is a demand, there can only be a quality supply for society as a whole and not just individuals within due to the nature of a centralised system that lacks the ability to separate individual elements. While in terms of simple provision of supply however, it is now becomes a private good in that the centralised system as the ability to cut off that supply to individual agents within the system. These two notions may seem the same, but the basic idea is that while supply (private good) may be able to be restricted to those individual agents who do not conform, that same agent has the ability to benefit at any stage from a quality supply (public good) regardless of how that agents actions or usage have affected it.

If the simple provision of the private good is not sufficiently managed, then the quality of the public good suffers in that efficiency and quality of supply decrease due to over demand and lack of capacity as a result of other agent's free riding due to their ability to selfishly benefit at the cost of other individuals in the system. This joint centralisation of provision and quality of supply through the common relation of individual users connected to the grid system shows that while energy use is a private good, its nature as a common resource renders it in effect having the nature of a public good due to notion of a shared commodity open to miss use and abuse, hence if maintaining the security of that supply is a goal, then energy should, and can, only be viewed as a public good due to the cyclic nature of causal effects between private use and public good. This characterisation as a public good has both pros and cons, and as discussed in previous chapters, economists view competitive markets as optimal for efficient resource allocation. However, in the current centralised system, energy's nature as a public good has led to chronic underinvestment in generation capacity which now has lead to a knock on effect in the private good dimension while simultaneously reducing the public good as a result of various externalities, mismanagement, over consumption and ultimately "the tragedy of the commons" as is present in a closed loop. If assuming that energy is a public good, and supply security and generation are centralised systems, is it possible that the Vickery-Clark-Groves mechanism provides a possible solution?

* The notion of public vs. private good is particularly relevant and crucially important when weighing up the benefits of decentralised generation in the hands of private IPP. This relation creates antagonism between the desired public good factors and the required private good in terms of the investment. Which responsibility is primal would naturally vary depending on which side of the good you are on, and as such This relation is discussed in the case study, namely for the role microgrids have to play in balancing and integrating these differing dimensions of the energy system.

2.3.4 Vickrey-Clark-Groves (VCG) mechanism and its role as a centralised mechanism

If there are five potential investors but only three investment opportunities, how is it decided who gets an investment and who does not? Well simply it would be best to choose the three who will invest more! Even better, if investors are left to decide on the value of the investment, themselves without knowing what the other investors are willing to invest. If the energy resource is finite and over consumption is rife, perhaps this scenario is applicable above a certain arguable basic right base point when applies to the provision of energy. This is the essence of a VCG mechanism, which provides a socially optimal solution to a resource allocation problem when the agents are strategic (Yang and Hajek, 2007). A VCG mechanism maximises social welfare or economic efficiency, in that it selects the choice, which maximises the sum total of agent's utilities, it holds the characteristic that no individually rational agent suffers loses through participating in the mechanism. In essence, agents subject to a VCG mechanism pay for the damages they impose on society, and as such previous externalities imposed on other agents, are now internalised through the mechanism. In the current centralised system this has the effect of rendering the centralised controlled public energy system as being decentralised in security terms due to allowing agents the ability to maximise individual payoffs while simultaneously increasing social good without having to suffer the consequences of negative externalities. This reorganising of economic activities into hierarchies promotes the aims of sustainability while protecting the rights of the individual.

Use of a VCG mechanism has a bi-dimensional role that of addressing the issue of resource allocation as well as providing a means for the efficient integration of renewable energy sources into the existing energy economy. Helping renewables to reduce their characteristic trait of fundamentally being a stochastic resource, which by nature is contrary to the ideal desired characteristics of traditional economics. Having an inelastic supply characteristic, renewables carry with them a disproportionately high risk of not being able to meet operating supply constraints. Meaning that, simply adopting Renewable energy technologies (RET) is not enough, installing smart infrastructure is not enough, what is needed is higher operational levels capable of balancing traditional and RETs. This brings to the light the increasing requirement of information and spatial constraints when adopting RET into traditional grid supply. A mechanism employed needs to reduce these costs as well as reduce the stochastic dimension through aggregating spatially diverse RET's. Incentivising RET adoption through penalty backed limitations on access to traditional energy sources, particularly when applied to spatial and operationally compatible consumers, through the use of a VCG mechanism potentially possesses the potential to counteract the limitations inherent in RET adoption and integration into the traditional grid system. A VCG mechanism carries a cyclic characteristic that utility functions will increase the greater the efficiency of the system to which the mechanism is applied. For example, those whose adopt and adhere to the mechanism will have an increasing utility function in relation to those who resist or are self-interested and non conforming, hence rendering the system as being self enforcing.

2.3.5 Adoption and diffusion of technology through the mechanism

In terms of emission volumes of green house gases, the largest drivers of increases are developing countries (IEA 2010). The IEA further noted that as of 2008, the total aggregate energy related emissions of developing countries for the first time, caught up and surpassed that of industrialised and developed countries. As Chow et al. (2013) noted, in early development stages, the demand for energy grows as a result of an improving economic climate. This is an unavoidable side effect of prosperity in economic terms; however, it reduces the objectives of sustainability to a mere side note. A rather large side note when one considers the IEA's 2012 statistic that 41% of global $CO2$ emissions are as result of the electricity sector. The GEA (2012) and the IPCC (2011) acknowledge that this is the greatest challenge facing global sustainability, going on to state that the solution for simultaneously curbing emissions, whilst still meeting global energy demand, lies in using current supply more efficiently as well as adopting renewable energy technology (RET) to support mans energy demands.

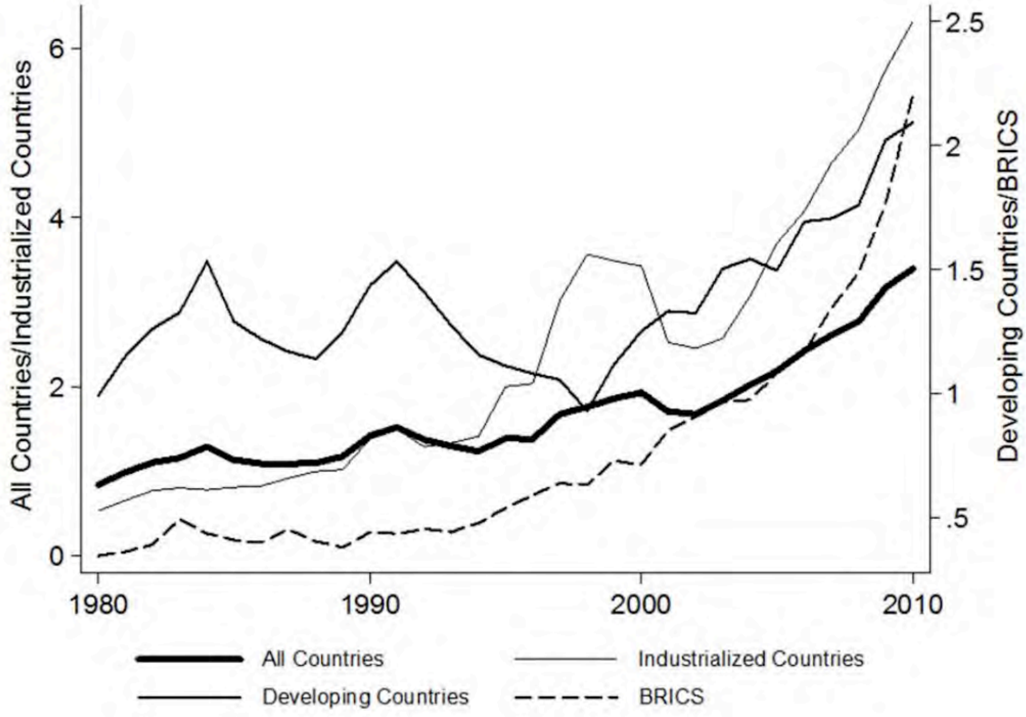

Figure 8: Share of NHRE (Pohl and Mulder, 2013)

Table 2: Summary Statistics on non-hydro Renewable electricity generation (NHRE) (Pohl and Mulder, 2013)

	1980					2010				
Variable	**Obs.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**	**Obs.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
Developing Countries										
NHRE SHARE	87	0.99	3.85	0.00	29.08	108	2.09	5.53	0.00	30.31
NHRE PER CAPITA	88	3.57	13.01	0.00	104.15	108	24.53	61.31	0.00	371.99
BRICS										
NHRE SHARE	4	0.35	0.70	0.00	1.39	5	2.20	2.65	0.14	6.64
NHRE PER CAPITA	4	3.91	7.82	0.00	15.63	5	51.90	65.89	6.80	167.44
Developed Countries										
NHRE SHARE	42	0.53	1.18	0.00	6.27	48	6.32	7.90	0.00	35.25
NHRE PER CAPITA	42	30.16	78.30	0.00	456.86	48	750.10	2106.26	0.00	14454.05

* Developing Countries' Statistics including the BRICS countries.
Source: Authors' calculations based on EIA (2012).

As Martionet (2012) noted, an increase in RET has the ability to help us meet our energy demands as well as having an additional positive socio-economic advantages in the form of, among others, increased access to energy and greater energy security. There are other advantages such as improvements in air quality, however in terms of this paper and has been the theme throughout, RET's role in enhancing energy access as well as advancing improvements in energy security are fundamentally the underlying aims. With the right mechanisms and systems in place, an improving economic climate does not have to imply, with almost an inevitable certainty, in the side lining of sustainability initiatives, whilst on the other hand, congruently advocating sustainability objectives does not have to come at the expense of economic growth. As figure 8 and table 2 highlight, RET levels are remarkably low amongst both developed and developing countries, however recent trends have shown an increasing adoption of RET in developed countries more so then developing countries, contrary to past historical trends of industrialised developed economies being founded on the backs of access to readily available, and large quantities of cheap fossil fuels. This difference in adoption levels is due to the idea that Popp (2011) refers to as being "*locked*" into a benign out-dated technology through vast investments in out dated technology for often the simple reason that at the time it was more cost effective or there was a lack of information creating uncertainty on the potential for the RET. A VCG mechanism in the right system as the ability to increase the percentage of RET in the energy mix for a developing country in that it uses its biggest asset, its inhabitants and their private aims, to facilitate the adoption of RET, for not just individual benefit, but broader societal welfare increases.

2.3.6 Technology adoption and diffusion is just the beginning.

RET and any technology that is a fundamental shift from the norm requires a subsequent shift in how to deliver, administer and assess that technology. An ultimate lack of acceptance results in less then ideal levels of adoption and diffusion of what, in technical terms is a fundamentally viable option. Further to this idea, Pool (1997) argues that technical superiority is, in fact, not even the most important factor in technology adoption. Segal (2004) goes on to further highlight that adoption and the related subsequent post adoption effects are inherently linked to a complex web of factors such as that of economic, social, institutional and individual factors creating a web of influence beyond purely technical superiority. Rogers (1995) in the Innovation-Decision Process Model, showed in figure 9, highlights neatly that technology adoption is a complex process, occurring over time and not in a single act.

Table 3: Innovation decision process (Rogers, 1995)

Each step in the process either facilitates advancement to the next step in the sequence or alters the outcome of the subsequent step positively or negatively. In step 1, knowledge develops an understanding of the technology; then this knowledge (step 2) manifests itself in the form of either a negative or positive persuasion, guiding and ultimate decision (step 3) on adoption or rejection (step 4) adoption resulting in implementation and the subsequent (step 5) confirmation of weather the technology achieved desired results guiding the decision of weather to carry on using or expanding use in adopting a technology which was previously rejected. Another important component of Rogers' work was his categorisation of adopters according to when they are most likely to adopt a technology.

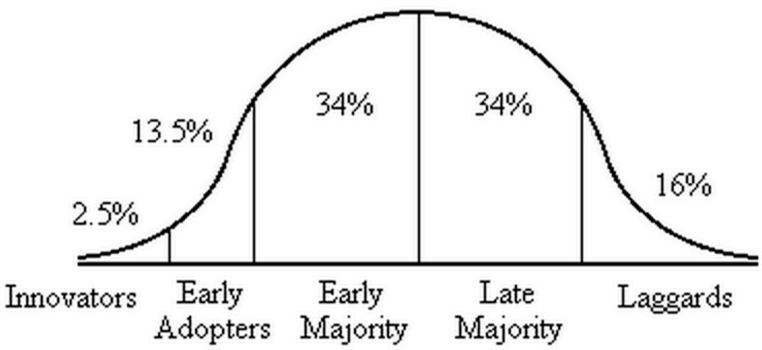

Figure 9: Hypothesized distribution of adopter categories within a typical population (Rogers, 1995)

Central to this categorization and the reasons for falling into each segment is the concept of perceived attributes (Rogers 1995). Perceived attributes being the opinions of potential adopters, formed as a basis for decision making, moulded from five key attributes, namely relative advantage, compatibility, complexity, trial ability and observability. In a closed system these attributes would create a complicated decision process, which in itself would hold the potential for generating a large proportion of negative opinions affecting adoption rates. However, in a complex energy system reliant on RET adoption to ensure sustainability, arguably now, of greater concern, is the efficient implementation and overall institutionalisation of the adopted technology.

2.3.7 Implementation and institutionalisation of RET

Implementation is "*...the actual use of an innovation in practice*" in another perspective referring to"*...both the content and process of dealing with ideas, programs, activities, structures, and policies that are new to the people involved*" (Fullan, 1996). The notion of the role of implementation is clear when it comes to the simple fact that replication is needed to ensure an adequate successful level of RET adoption. However, this purely replicative adoption of RET based on previous adoption results is ultimately a barrier to increasing levels of future adoption due to inefficiencies inherent as a result of variations in the outcomes of the application between differing stochastic environments. Reducing these inefficiencies relies on modification and alteration of the RET for local environments; this approach to implementation based on replication is similar to the ideas in the following chapter with a focus on behavioural learning aspects. Fullan termed this " *mutual adaption*" where in essence the technology is rendered more efficient due to a greater focus on how it is implemented in that localised setting vs. blind adoption. Ely (1999) put forward eight conditions for successful implementation.

- Condition one: Dissatisfaction with the status quo: Creating the environment of perceived stagnation in relation to others driving desire for advancement. This can either be innate or induced through a mechanism;
- Condition two: Existence of knowledge and skills: Without this regarding the RET the appropriateness of the technology is questionable and thus now has the potential to crease dissatisfaction;
- Condition three: Availability of resources: Fundamental in making implementation work;
- Condition four: Availability of time: In order to acquire knowledge;
- Condition five: Existence of rewards or incentives;
- Condition six: Participation and shared participation in decision making;
- Condition seven: Commitment: In the form of endorsement and continued support for the RET adopted;
- Condition eight: leadership: In the form of a figure or organisation directing the process.

These conditions are facilitating mechanism for the successfully implementation of RET, increasing not just levels of adoption and diffusion but concurrently the system efficiency due to aggregation of these technologies. Successful implementation induces the final level in the technology cycle in the form of institutionalisation of RET in the system. Miles et al. (1987) refer to this as "*...an assimilation of change elements into a structured organization modifying the organization in a stable manner... a process through which an organization assimilates an innovation into its structure*" simply the technology is routinized through successfully implementation, due to it now being characteristically integral to the organization or the social system and is no longer considered to be an innovation or novelty. The previous status quo has now been replaced by that of a (in this case) RET which due to the cyclic relation of feed back loops results in increasing levels of adoption of the technology consequently in future decision processes. This, however, does not imply that diffusion will increase as result merely that adoption increases. In the current centralized monopolistic system, sustainability ultimately relies on total Diffusion of RET, due to out equal access to the common and thus our aggregated actions required in averting the tragedy. However, as the next section shows, income inequality (alongside institutional constraints) represents the largest barrier to total technology diffusion and as an effect broad scale adoption, but contrary to that view, I promote that this limitation represents the greatest potential justifier for the new model developed in the final chapters.

2.3.8 Using income inequality to promote the adoption of a limited VCG mechanism

A common method to increase technology diffusion is the use of a market based pricing mechanism based on the back of subsidisation of the technology. Subsidised green technologies are not a new novel idea; they have been implemented and arguably have failed in their aims. Technology diffusion through subsidisation has the self-defeating characteristic of exponential growth. A large injection of subsidies will lead to an increasing adoption rate, however that increasing adaption rate ultimately produces an unavoidable and paralysing financial burden, that is unable to be indefinitely met and thus the subsidies inherently are withdrawn once again, limiting adoption of the technologies just as it was starting to proliferate. Another side effect of subsidised based diffusion in a stochastic environment, is the creation of uncertainty of future returns and the potential for RET costs reaching grid parity, this uncertainty ultimately reduces investment from the business community in further RET beyond that which was adopted in the subsidised phase, ultimately manifesting itself in a negative confirmation phase in the evaluation of a RET. Creating certainty and stability in the renewables market is the underlying aim of applied mechanisms, but should these mechanisms, along with the inherently required incentives, be applied in blanket fashion or should they there be a targeted approach, focusing on increasing adoption and diffusion of RET in specific sectors of society? This implies that societies energy sustainability relies on focusing on specific strata's within the collective, for whom RET holds the highest appropriateness, to drive the change while providing societal improvements to the public good and welfare concurrently. In the scope of the broader economy, RET are fundamentally a consumer good; hence the determinant influencing diffusion is the income inequality gap (other determinants are educational and geographic, however the initial focus is primarily on income). Why focus particularly on the restrictive income determinate, and why is technology diffusion so important? Heathcote et al. (2010) argued convincingly for the notion that, the degree of uncertainty about the future economic outcomes decreases as the share of economy employing new technology increases. Hence focusing on the income gap determinate enables us to effectively increase diffusion amongst the portions of the economy that are primed for adoption and hold the necessary means to invest in an uncertain deviation from the status quo due to the creation of greater certainty in the technology and its potential returns.

As discussed in earlier chapters, traditional economic theory describes consumers as homothetic, in that their individual preferences and derived utility are a function of a budget constraint. Holding the view that aggregate demand is in relation to aggregated income levels, such as increasing income levels, or decreasing costs theoretically will increase demand. However, if one were to instead look at individual incomes, and understanding that individual consumers will alter their allocation of income between goods as a result of their individual income. It is evident now that those in the higher incomes levels will not only consume more then poorer income levels, but will spend a portion of their income on good which those in poorer income levels would not at all. In essence, income distribution now has an effect of aggregate demand whereas in the traditional economic views it does not. Why is this notion important though? For the simple reason that new technology is often viewed as a luxury good and not a basic need. In the case of RET this view hampers not just adoption levels on an aggregate scale, but diffusion levels in a broader societal level. Changing this view of RET from a luxury good to a basic need is not entirely feasible in the lower income levels due to the budget constraint, however focusing a mechanism on higher income levels, turning RET from a luxury to a basic need through either incentives or the threat of negative internalities has the ability to increase aggregated adoption levels and diffusion amongst the percentage of society who consume above their share of the common. This increased diffusion and adoption of RET will have a cascading effect of increasing access to quality energy in lower income levels further increasing their potential to advance in society and contribute to increasing economic gains.

Chapter three Literature review Part II: Why being effective is more powerful then being efficient

"*The Tao begot one, one begot two, and two begot three. The three begot the ten thousand things. The ten thousand things embrace Yin and express Yang. Harmony is achieved by combining these forces*."

- Tao Te Ching

3.1 Rationalising an Autopoietic system form in Moving away from the classical approach

"Control can be obtained only if the variety of the controller is at least as great as the variety of the situation to be controlled" (Skyttner, 2001) first proposed in 1958 by Ashby, the law of requisite variety at its core, in systems theory, promotes the idea that control of a system provides a platform for system homeostasis and performance. This is as a result of the controller having the ability to prevent variety being transmitted from the systems environment to the system itself (Richardson 2004b). On the other hand the darkness principle in complexity theory, centres on the notion that no system can ever be completely known. The source of this darkness is what Cilliers (1998: 4-5) describes as arising as a result of each element in a system being "*…ignorant of the behaviour of the system as a whole, it responds only to information that is available to it locally. This point is vitally important. If each element 'knew' what was happening to the system as a whole, all of the complexity would have to be present in that element.*" On paper this darkness principle would seem to nullify that of Ashby's law of requisite variety. But is that the case? In the classical sense of the proceeding Part I yes. This is as a result of the classical notion of total control of a system residing inherently in the ability to achieve a pre-determined outcome. But if instead now in the adoption of systems and complexity view, total control ceases to exist as being pure control of the whole but rather takes the form of a bounded view of the parts of the system, which as a functional characteristic result, facilitates the development of robust interventions. This process is more akin to a focus on defining the problem, vs. attempting the description of the desired outcome.

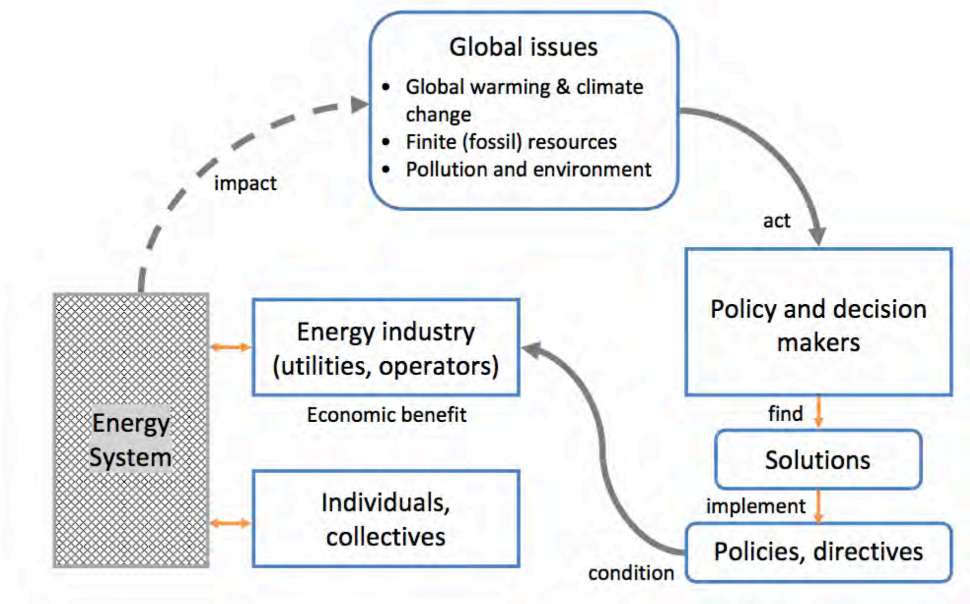

Figure 10: Global framework of the energy system (Kremers 2012)

This chapter focuses on providing an overview through briefly merging and creating an understanding of system theory and complexity science, promoting the ideas and principles within its structures as the modern solution to creating a sustainable socio-technical system which will be applied to the case study later on. This, as will become evident, relies on embracing a systems understanding while adopting the characteristic functionality of dynamic complexity, which is inherent in open systems.

3.2 Effectiveness vs. efficiency and the difference in systems

Being sustainable implies having the ability to indefinitely carry on an activity, having an efficient system, which the previous chapters on game theory and mechanism design advocated for, does not represent the fundamental sustainable characteristic of an indefinite functioning ability. Being efficient is merely the ability for a system to correctly apply the inputs. In the neoclassical economic view as discussed, efficiency is optimal when all agents rationally promote their self-interest in increasing their individual utility functions. This is primarily as a result of consumption. Thus, in essence, an efficient system is one, which has the characteristic of using the maximum of inputs in the form of available resources. In energy terms, at the micro level of an individual this translates into the form of increasing consumption ability. If an individual is more efficient in how the use energy then a direct consequence of that efficiency is that individual's ability to use more and as a result increase their individual utility functions thus ironically (in sustainability terms) the system becomes ever more efficient. Thus this ability or characteristic of being efficient does not imply sustainability as it lacks the intergenerational ability for an indefinite action. Being effective on the other hand implies the system achieving a higher level of result as a consequence of actions within the system. In general a system is evaluated on whether the resulting outputs have achieved the desired objectives. This does not imply that the two concepts are mutually exclusive. Inefficiencies in the system can contribute to decreasing effectiveness, while efficiency fundamentally has no meaning in the absence of effectiveness. That is to say that no amount of efficiency can compensate for a system that is no longer effective. In that, it is the collection of actions that embody the goals and aspirations of the system components, which define effectiveness that no amount of finely machined system efficiency can replicate. Effectiveness results not as a pure function of the structure and architecture of the system but as a result of the actions with which that structure facilitates. In essence, the architecture defines the framework of understanding, acting as an enabler of efficiency and effectiveness. Having an effective system is reliant on almost “breathing life” into the system through enabling actions and their effects having an essential impact on the quality of the systems output. This quest for effectiveness over efficiency is at the heart of systems theory and will be continually alluded to throughout the preceding chapters.

3.3 Systems and why they are important

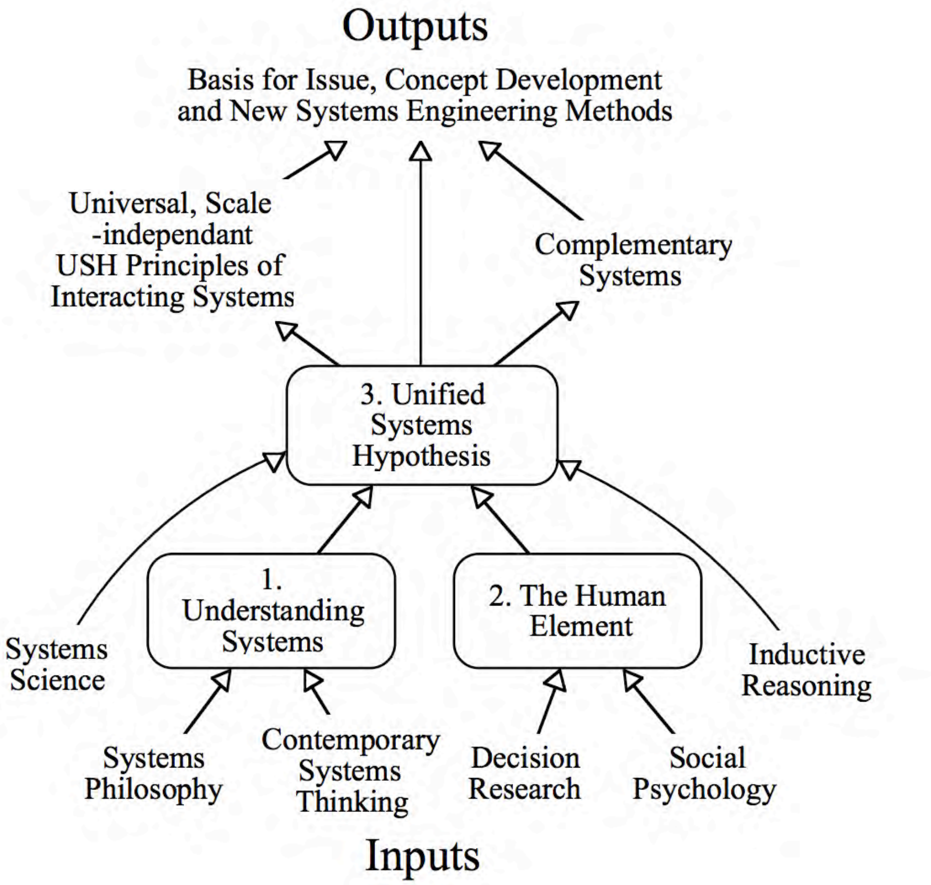

Figure 11: A systems perspective (Hitchins, 1992)

Derek Hitchins (2008) rather eloquently and simply states that "*A system, is a whole something*" while simplicity itself, this is the fundamental essence of what a system is. Neglect a portion of something and the whole ceases to exist, as it is incomplete. Systems theory or thinking which developed, from the idea of homeostasis, or the maintenance of a dynamic whole in order to maintain the systems working conditions is vitally important in creating modern energy systems robust enough to meet inter-generational requirement without compromising current functionality. Systems' thinking is about delivering quality, through integrating all aspects and interests within a system consisting of multiple interacting components (Blockley, 2010). The predominate ideas within classical thinking is that of breaking a system down into its constituent components as a means to better understand the system through an enhanced understanding of these individual components. This approach is replaced in systems thinking by a broader more encompassing focus on how the individual components being studied interact with the other constituents of the system particularly when the problem is a complex one as a result of the dynamic complexity of the system itself. Traditionally individuals think linearly, relying on the comfort of cause and effect inherent in that of linear causality. Senge (1990) takes the more dynamic viewpoint in stating that systems thinking is about thinking in loops and searching for connections and feedbacks in systems. A systems ability to create loops in its dynamically interconnected structure of the whole, produce an interesting consequence of the whole being a greater functional entities then the simple aggregation of its parts. Why this is possible goes back to the fundamental attributes of a system.

In defining a system you need: (1) components (2) mutual interactions (3) the environment the system is situated in and finally (4) a boundary, which distinguishes the systems from its environment. There is a general and fundamental primary property of interdependence between parts and variables in a system. Parsons (1951) highlights that interdependence is as a result of the existence of determinate relationships amongst the parts or variables in contrast with the randomness of variability. This means that fundamentally, interdependence is the order in the relationships among the components that enter into a system. This order has the tendency to tend towards equilibrium. This equilibrium however need not be stable in the truest sense, but merely an ordered process of change, which follows a determinate pattern rather than random variability, in other words, growth through homeostasis. It is the growth ability through interconnectedness, which makes a systems, approach highly powerful yet intriguingly difficult, as a result of the assumptions in the proof of the system as whole having definable properties not pertaining to any of its parts. These assumptions fall into the categories of constitution, adaption and reproduction which together have the overall outcome of complexity. It is these three categories of assumptions underpin the following chapters and the case study

- Constitution is the fundamental idea that systems collect and organize elements that are already there. Either in the form of the bottom-up type pre-existing components, or the top-down constitution from a previous stage of the system into its components. This top-down constitution exists in the form of constraints on initial conditions and the phase space of the system components, as well as development of organisational layers.

- It is this development of organizational layers, which is a structural requirement condition for the development of adaptive systems. Beyond this facilitating condition, an adaptive system needs (1) rules which govern the systems interaction with its environment and other systems as well as (2) the existence of a higher order layer which can change such rules of interaction. Either if they are random, acquired patters or as a result of pre-established patterns. It is this adaptive ability, which creates the characteristic of persistence over time due to a form of dynamic stability termed multi-stability. This multi stability is the dynamic ability of a system to prevent system destabilization in the face of perturbations.

- The assumption of reproductively is perhaps the most important one in that it deals with system continuity through time. Particularly consequences as a result of a new component either entering the system or being generated internally, as well those consequences of components exiting the system. The problem of reproduction is inherently linked to the theory of Autopoietic systems, and it's this theory in particularly which was the driving force for the case study and the investigation into how our current energy system is structured.

3.4 Autopoietic systems

The ideas contained within autopoiesis thought originally developed from the field of biology and revolve around the notion that biological systems are characterised by a circular, recursive, self-referential, mode of operation (Sharon 2009). Interpreting an energy system along the lines of living biological systems is inherently difficult and flawed particularly in respect to the appropriateness of the transposition (Luhmann, 1989). Luhmann had great difficulty in justifying the metaphorical transfer of the ideas within autopoiesis thought from biology to a general systems application however he made sense of this through the point of view that individuals readily grasp concepts by comparing them to known objects. Thus meaning is not given or related to anything; meaning resides within the difference and context. Moreover, significance does not lie in the root of meaning, or the field in which the observation came to be. (Sharon 2009). Significance only lies in the significance given through the on-going creation of meaning within particular outcomes. Thus meaning relies on it perpetually being autopoietally created and recreated. In systems theory, this autopoiesis concept is important in that as a concept it stresses that there is a form of relationship between a system and its environment.

The concept of relationships between systems underpins system theory and alludes to systems being open to their environment. If one were modelling an open input-output system it might characterize the relationship between the electrical energy system and social system (part of its environment) the constraints on the energy system directly impact the social system and social interests impact the energy system. In this model we can look for the presence of the intervening system on the other. If one were to go a step further and adopt an autopoiesis approach in the form of organizational closure, it takes the relationship between system and environment, from directly causal to one which focuses on the effect of the internal working of the system. Fundamentally a system, which is organizationally closed, refers to "systems that rely on their own network of operations." – and so not only any external input – "...For the production of their own operations, and in this sense, reproduce themselves." (Luhmann 2004, pp.79-80) This means that in an auto poetic system the evolutionary trend is paradoxically dependent on simplifying information from the environment and not being open to it. In other words, the accumulation of internal complexity within the system is as a result of the system creating order from the externalities generated from its environment. Organizational closure amounts to the set of conditions which amount to systems self-reliance in the form of self-organization of structure plus that of self-regulation. As a concept autopoiesis shifts thought from solving problems or disputes generated by the system and its environment towards producing processes, which are aimed at producing communication (in this case) between electrical systems which can resolve those problems. This shifts thought of electrical systems from consideration of relations of other systems towards a self-generating recursive system. What does this mean in terms of an electrical system?

A fundamental outcome of a system having organizational closure is that while the system is open and able to interact with its environment, it is closed from an organizational perspective yet in constant interaction with its environment (which can consist of other systems). The system is fundamentally structure determined, and changes in the system are triggered by environmental disturbances. Not determined by them. Thus it is the structure of the system, not the disturbance that determines the change in the system simply if the system is incorrectly structured, then an external disturbance will not be correctly distributed throughout the system, hence this is a failure on the part of the system and not as a result of the external disturbance. Overtime this system view implies that the system will adapt to its environment. This ability is as a result of a process whereby the system undertakes a form of structural drift in responding to successive perturbations according to its structure at any given time. As a result of this characteristic, unities and couplings arise among the system network as a result of congruence between onto genic structural drifts of systems with the same level of order. This results in reciprocal coordination triggered as a result of the emergence of structural coupling and structural drifts in the energy system. And not as a result of a mechanism applied to the systems themselves that reacts to a predesigned system perturbation. It is this ability in autopoiesis systems for self-referential re-productivity, which enhances the system's ability to persistently exist as a network of systems, even when components are added or extracted from the system. This creates not just an efficient system, but on that is effective and sustainable in the long term.

3.5 The future of socio technical systems: Embracing complexity and systems theory

"If social worlds are truly complex, then we might need to recast our various attempts at understanding, predicting, and manipulating their behaviour. In some cases, this recasting may require a radical revision of the various approaches that we traditionally employ to meet these ends."

- John H. Miller, "Complex Adaptive Systems: An introduction to computational models of social life"

The section on game theory concluded with the understanding that sustainability's failure will be as a result of societies current negative externalities produced within the energy environment, while the chapter on mechanism design came to the conclusion that mechanisms have the ability to efficiently promote sustainability objectives without compromising individual utility functions. Thus, if neoclassical economics, incorrectly, advocates freedom and pure competition for resources, as Pareto-optimal, while mechanism design contrastingly shows that some form of "device "or intervention, which balances utility and system efficiency is in fact the Pareto-optimal method, perhaps then the ideal solution lies blending the game theoretic and mechanistic principles. Perhaps, then, the natural and man-made system will be efficient, but what does this efficiency imply? An efficient system merely implies that the inputs are used in the correct way by the system to increase productivity of the system itself. But is this sustainable? Simply put, no. To be sustainable the system needs to be effective as well, being effective implies that the system achieves an output, which is desired, or good. Ensuring the highest utility for the system users means that the system needs to be efficient and effective.

Achieving this, I argue is reliant on allowing for complex properties such as emergence, self-organization and micro behavioural characteristics to induce system wide properties, which exceed that which is possible of its decentralised individual agents in isolation. Facilitating not just the spread of RET and sustainability initiatives, but increasing the effectiveness of system changes with the aligned congruent positive benefit on the associated social system as a whole, through the advocating of the primacy of social welfare. If the energy system along with the sustainability objective, is truly complex, then by chance the lack of a viable solution is down to our fundamental lack of understanding of the dynamics of a complex system and by relation to the basic notions of systems themselves and the underlying potential which exists within our actions and beliefs. In essence "*To us, complexity means that we have structure with variations*"(Goldenfeld and Kadanoff 1999, p. 87) perhaps more ambiguously (or mystically) "*Complexity starts when causality breaks down*" (editorial 2009). It is this variation within our system structures, the divergence from traditional economic and rational based principles, which holds the potential to either restrict sustainability attempts or, if embraced, potentially hold the key to enabling sustainability's success. At the core of this chapter is the understanding of Complex Adaptive Systems (CAS), its theory holds the notion that complex systems cannot be fully engineered and understood from the "top down" due to the principles of shaping, variation and selection. Not unlike a natural system an engineered system will respond in a dynamic manner, generating viable options, which in turn as a consequence, influence the environment resulting in selection or rejection and thus a form of evolution.

In building on the previous chapters, I view CAS's as a form of transition mechanism, perhaps the use of mechanism in this context is misleading; transition facilitator is probably more apt for this chapter that fundamentally challenges mechanistic approaches. Transitional, in that as a system it is able to promote RET and sustainability practices, from theoretic solutions to that of established practices, whilst increasing the effectiveness of the energy systems as whole. Targeting resources and technology on a system designed correctly, correctly in that the correct structures exists as well as a fundamental level of "appropriateness" for the technology is inherently present, will avert the scenario (Mitre, 2008) likens to the situation where a capability "*thrown over the wall*" to the user is much more likely to suffer from stasis and be passed by as conditions change. In essence, I view this approach akin to designing a bridge now, with the forethought of the addition of a second level in future periods that is able to accommodate future expansion, yet conform to current cost or design limitations. This approach reduces the obstacles in applying sustainability objectives to society as a whole. This is through the incremental adoption of technology or process as needed, but nonetheless this incremental adoption does not impede the successful future outcomes as a result of system advances and changes. Fundamentally more important then reducing obstacles to sustainability incentives is aligning the engineered system within the confines of the current systems so as to promote its temporal continuity or simply, the reproduction of its patterns of actions consisting of roles and actions for future generations to replicate and adopt. However, beyond all that, complexity expresses the cognitive limitation individuals posses in the face of the self-organising and systematic nature of the world.

3.5.1 What is complexity?

If one were to take any two models (or perspectives) of a system, they will reveal information regarding the systems that are not entirely independent or entirely compatible with each other. This complementary law (Weinberg, 1975) formed the basis for the statement that a complex system is a system that has two or more non-overlapping descriptions (Cohen, 2002) Fundamentally implying:

1. A complicated system exhibits linearity and has one optimal solution;
2. A complex system exhibits non-linearity and can have multiple optimal solutions.

Perhaps simpler then this notion and one that is the more widely understood is the systems holism principle with its roots amongst Aristotle's understanding that "*The whole is greater then the sum of its parts*". While a bit misleading in a literal sense when applied to a system, the basic idea and understanding that parts in isolation will, and do, behave differently than when they are connected to an environment, and likewise the system environment behaves differently than the mere abstraction of its parts. It is this notion of complexity that exhibits the greatest potential for developing a more efficient and effective energy environment. However, is complexity merely a mental reflex, or a function of interconnected systems? Scott Jackson (2012) asked the question weather complexity was objective or merely subjective. Subjectivity is usually argued with the view that if something is difficult to comprehend, then it must be complex. The ISO supports this view in defining complexity, as "*the degree to which a system's design or code is difficult to understand because of numerous* *components or relationships among components*". A neat and subjective definition of complexity, which inherently relies on an objective description of components in order for the definition to hold relevancy (ISO 2009). Thus, a rather weak argument for the subjective nature of complexity in that it likes lacks enough details to allow for a quantitative analysis of complexity. This lack of quantitative ability produces the inescapable issue of the subjective view not providing an adequate platform for which to engineer complex systems from. Going back to the previous section on complicated vs. complex and applying the subjective view to that of a clock for an example. It is subjectively clear that the clock is complex in that the average person does not know how it works, yet the machine itself is near perfect in that the individual components are highly machined and each have a specific function rendering it as a consequence of this perfection merely complicated and not objectively complex, even though we do not understand it ourselves.

Analysing complexity form an objective viewpoint involves dividing the measures into two categories namely structure and uncertainty. (Marczyk 2011). Structure being the number of components and interfaces while uncertainty deals with the probabilistic distribution of the relationships between components in essence the variability within the system. Shannon (1948) used the term "*information entropy*" to describe the variability category of complexity. In essence, this pertains to the uncertainty in the value of parameters describing a relationship between two or more elements. This definition introduces the three parameters that define complexity: (1) Number of elements (2) number of interfaces (3) variability. It is a system's variability, which shifts that which is complicated, to that of the complex. Thus, within the structural and uncertainty categories, it is the variability within a system that acts as an inducer of complexity, while structural effects determine the degree of complexity. It is this objective notion of complexity that will be referred to throughout the following chapters, with the use of Boolean networks as a means of simplistically illustration the idea within the text.

3.5.2 Why complex adaptive systems?

The aim can arguably be pure Revolution, well, more of a revolution in our understanding towards the behaviour of systems rather then developing a new technology capable of solving current and future issues. As previously discussed a system is inherently complex as a result of the fundamental characteristic of many inter connected parts required to act in unison. How does a system become adaptive? And why is an adaptive system ideal in the first place? At its core, an adaptive system is one where there exists a feedback structure, which bestows upon the individual's agents the ability to change in ways, which will enhance their survival within a stochastic environment. This relies on the presence of similar and partially connected microstructures whose engagement alters the macro environment and reciprocally this alteration of the macro subsequently alters the actions at the micro level, resulting in a cyclic feedback loop.

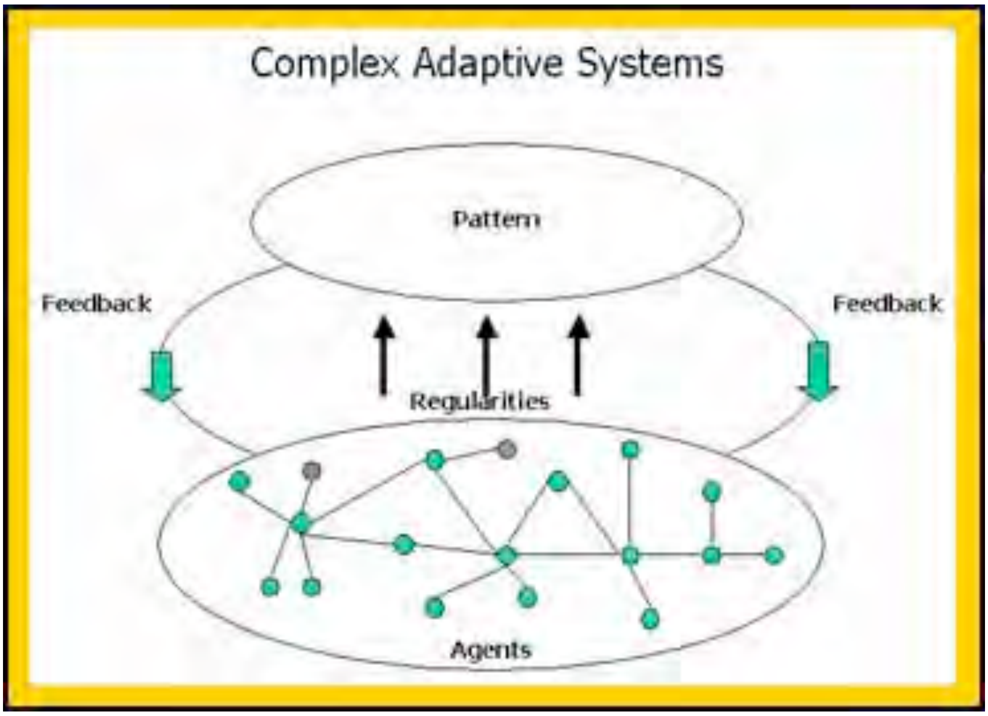

Figure 12: CAS with cyclic feedback loops

Fundamentally all successful (and these are the ones we are interested in) are *open systems*. Existing within their own environment, and are also apart of the larger environment, thus as the environment changes the systems need to change to ensure best fit. This results in the Darwinian notion that changing to ensure environmental fit subsequently alters the environment within which they are a component, resulting in further change required as a result of the change in the environment, producing a constant change process. Similar to the ideas of evolution, however fundamentally different in that an adaptive system does not rely on learning to drive change, just an adaption to its environment. The absence of this learning requirement produces the sub-optimal property of CAS, namely the idea that CAS does not have to be perfect for it to thrive within its environment (Fryer, 2009). It only has to be better then the constraints placed upon it, and once it reaches a state deemed good enough, it will trade efficiency for greater effectiveness every time. Why is this trade off important? Efficiency and effectiveness are two distinctly different ideals, its possible to be efficient without being effective. The system will chose the means best suited to ensure survivability, however this does not imply that it will be effective in achieving sustainability objective or effective in resulting in greater public good. Therefore this suboptimal property of CAS systems in explicitly crucial in ensuring long term attainment of stated goals. Further properties of CAS systems are:

1. Requisite variety: embodying the ambiguity and paradoxical nature of CAS systems, requisite

variety implies that greater variety results in stronger systems;

2. Connectivity: relationships between agents are more critical then the agents themselves in a CAS system, how agents relate and connect within the system is vital to the survival of the system itself due to these connections facilitating the feedback and formation of patterns within the system itself;
3. Simplicity: again a paradoxical property of CAS systems is the notion of simplicity, while the system itself may be complex, it is not complicated, and the rules governing the system are simple.

These properties help understand the notion of CAS, however, the properties that are of true importance and will be discussed further are (1) Emergence (2) Self-organisation and (3) learning. While a learning function is not a prerequisite for an adaptive system, from an agent perspective an increase in learning or simply an enhanced information framework has the effect of increasing adaptive characteristics and as such will be discussed in this chapter for its role as a facilitating adaptive function.

3.5.3 Supporting Emergence

Embracing a systems thinking approach based on complexity is what I argue as being the greatest tool in achieving sustainability. Moving away from placing a focus on the nature of individual agents within a system towards a focus on the relationship between these agents is able to give attention and focus to long-term effects. This system approach is able to give an active role to agent in the system that is an observer and is thus able to account for an agent lacking scale in relation to aspects of the system he is blind to. But where does emergence fit into this? Emergence can be likened to natural selection in evolution theory; it is the fundamental driver of systems theory.

3.5.4 The Micro level: Human factor

As a complex system consists of multiple agents, arranged in structures at multiple scales and whose process of change is not reducible and describable at only one level, this irreducibility often creates the impression that one is studying complexity when, in fact, they are studying only the complex system without actually studying the underlying complexity present. Understanding complex systems does not inherently rely on an inter-disciplinary approach; a physicist studying a social network is not an example of inter-disciplinary research, in that he is not contributing anything beyond his proficiency in applying a method to the problem. In a socio-techno system of energy use, solving the complex system or understanding the underlying complexity is reliant on drawing in the knowledge base from multiple disciplines in order to understand the dynamic relationships present at the micro and macro level. This distinction between the micro and macro levels requires an altered approach when attempting to research the complex relationships present. With micro level complexity revolving around behavioural rules and the macro level incorporating environmental constraints, in the form of institutional, spatial and structural parameters, advocating an epistemological perspective approach to researching and understanding not just the complex system but the underlying causes of the complexity represents a paradigm shift from the norm. This epistemological viewpoint is often in conflict with the ontological viewpoint in that there is no clear agreement on how the micro and macro levels interact and, thus, how emergent properties develop or affect each level. With energy use and the quest for sustainable development being an intrinsically social problem, this disagreement means that developing an understanding of the socio-technical system is heavily reliant on our views towards the research itself. This intrinsic openness with regards to the potential for varying interpretations on the externality of the world itself and of the micro and macro components of the complex system neatly highlights the potential inherent within the framework of a complex setting if the correct view is held when attempting to embrace such a system.

In order to address current and future shortfalls in grid supply of energy a new direction of thought and structure needs to be embraced. As outlined earlier, an energy policy needs to address climate related issues as well as have a strong focus on energy security and affordability. A proposal is the moving away from rigid linear policies detailing what needs to be done to ensure sustainability, towards a non-linear dynamic method of advocating what is possible if sustainability is achieved. This shift in thought turns the idea that the collective is a cognising agent, into the collective consisting of cognising agents. This represents what is fundamentally a shift from the macro towards a description of the micro level based on causative assumptions and complex characteristics such as emergence and self-organisation.

3.5.5 Complexity and role of rationality

In the earlier text, the idea of rationality was propounded for the effects our own individual beliefs, ethics, and actions are moulded and shaped by the idea of rational thought within the framework of game theory thinking and within the role our rationality plays in sustainable development in the confines of a socio-technical system. Rational intelligence has its antithesis in the form of irrationality; the term intelligence in this case is used to account for our actions beliefs, ethics, motives etc.

In effect our existence can be based on our intelligence and our response to internal and external causal effects. However, there is a clear ground present between that of rational intelligence and that of its counterpart irrational intelligence. Non-rational intelligence or thought, is not a counter balance to that of rational intelligence, it is merely a non-linear intelligence incongruous with logical rational intelligence. Understanding an object presented to us, or in the case of everyday decisions, the link between our actions and the consequences, rationality is used to account for potential outcomes. Nevertheless in a socio technical system, which is inherently complex and non linear, this linearly rigid rationality is in contrast to the multi tiered level of thought inherently required when an individual's sensitivity to their own tangible reality is incomprehensible for another individual who is not within the bounds of the others reality. Where in the past rationality was found to be self-defeating in that irrationality was required in order to achieve the desired outcome, complexity affords non-rational thought a platform, which is congruent to logical actions and aims. This idea allows an explanation for the social character of actions developing towards emergent properties previously unexplained in liner models and which as will be discussed later, potentially possess a viable means of pursuing sustainability objectives without broad blanketing control or institutional structures. But if rationality in traditional economic terms is now not generally self-defeating, and has the ability of inducing emergent characteristics, is there a system requirement to rendering these traits more then a mere quirk? Chapter 6.2 highlights the role of various dimensions in answering that.

3.5.6 The Four fundamental theories

Facilitating the development of an adaptive, evolving complex energy system is reliant on a multitude of conditions drawn from an understanding of multiple theories. In summation, after having discussed various topics in the preceding text, I draw views from the below four theories, in the aims of formulating what I foresee as being the best possible means of attaining sustainability.

- Economic theories: Where energy is viewed as being a commodity and users adapt habits based on pricing mechanism, for example very simply expressing that increasing price will lead to a decrease in demand;
- Psychological theories: Where energy use was viewed as being affected by stimulus response mechanisms and through the engagement of agents in the system;
- Sociological theories: Where energy use was ultimately viewed as a system and daily habits and actions are significant. In essence it views energy use as being a side effect of our daily activities and not of the view that individuals directly consume energy;
- Educational Theories: Where we were finally viewed, as being individual and that energy use is a skill shaped and altered by our everyday experiences.

Clearly each theory holds a different view on what energy use is really is; however this complexity in the multi faceted means of comprehending energy and its use allows for a multiplicity of possible outcomes, each with not necessarily a negative outcome but each lacking the possible best case scenario. The term “outcome” is used over “solution” as ultimately the idea of a solution is fundamentally flawed in that there will always be a better scenario, particularly when dealing with the issue of sustainability. A nice representation of this is in the view that humans within a complex system will, with time, develop complex thoughts to their views of sustainability of future generations to that of a positive change in their overall environment.

One commonality among the four branches is the development of the idea of what an individual is and how they position that individual within a system. There are two distinctly different views with varying effects of outcomes.

View one: an energy user is viewed as an *individual*. And in particular an individual who is rational in their choice and in the actions and manners towards other individuals. Their actions are seen as being a direct consequence of the information available, or the external and internal prompts exhibited on them. This guides their decision-making process ultimately resulting in the end action and the outcome of that action. In terms of the important characteristic of rationality, the individual has an interest in the outcome with a preferred preference of the various alternatives and who will make a decision that fulfils those preferences. This has the direct consequence of opening up an individual to high levels of uncertainty due to the reliance on knowledge of initial conditions and multiple unknown strategies. Economic and Psychological theories in general follow this view of what an individual is and represents what is in effect a linear model where the collective is a cognitive agent with its stimulus basis in the macro-level.

View two: focuses more on the idea of *interaction* and not process, moving away from the moment of decision, towards how a decision can be made to be inevitable due to the interactions at multiple levels on the individuals, setting conditions within which a decision is formed. This view moves away from the idea of focusing on the individual towards a focus on the actors within the individuals systems, which set conditions shaping those individuals actions. Educational and sociological theories represent this view towards that which is non-linear, dynamic model based on the importance of the micro levels drivers.

These theories in themselves are not useful in providing beyond an explanation of reality, for that a model is used to provide a simplified representation of a complex process. To that regard I shied away from an individualist model of behaviour in favour of socially oriented model of behaviour for energy use, viewing energy use and sustainability as an inherently social problem. And, thus, solvable through an aggregation of societal actions and not just as a result of centralised interventions or means.

3.6 The role of behavioural economics in the development of a Social relationship orientated behavioural model

The current energy climate should then not be viewed as a failure on the part of the person, and instead as a direct consequence of a failure in design. Neoclassical economics often finds its greatest challenge in behavioural economics; a simple example of this bifurcation from traditional views is the puzzle of why people will often risk/damage their long-term future for immediate gratification. Designing a system or developing an energy policy cannot use an individual or social deficiency, as a basis for an explanation of failure. Instead failure can be attributed to an inadequate design, which failed to either address or mitigate the potential for those deficiencies or variations. Hence designing an energy plan or grid model needs to factor in the macro social relationship dynamics as well micro behavioural characteristics of individual cognitive agents. Key to this idea is the role *information* and *interactive learning* plays. In an evolutionary system, learning alters the shape of the search space in which evolution operates; this has the side effect of allowing expedited evolution (Pollitt and Shaorshadze, 2011) facilitating and enhancing this interactive learning is key within the new proposed model. This moving away from technological and traditional neoclassical economic tools to address energy issues and instead focusing on a behavioural method is a possible solution to attaining desired outcomes. This, however, has different effects when applied to the residential and commercial sectors. The following case study is of a medium size business, a behavioural model for residential would be different to that of commercial, however the adoption of microgrids aiding interaction among the different sectors greatly enhances the potential for behavioural models for commercial as well as residential through aligning the aims and actions of the two different energy use sectors. However the exception to this would be a large commercial enterprise where approach based within the neoclassical realm would be more advisable due to their enhanced ability at making economic decisions in the face of economic restrictions in the form of potential future supply shortfalls and price increases.

3.6.1 Economic behavioural aspects

Differentiation from the traditional neoclassical models to that of a behavioural one requires certain aspects. Four main groupings are identifiable, which signify the departure from traditional to behavioural.

- Area one: Time varying discount rates;
- Area two: Prospect theory and importance of reference points;
- Area three: Bounded rationality;
- Area four: Pro social behaviour and fairness (Pollitt and Shaorshadze, 2011).

These four areas will be briefly discussed so as to provide a background to thinking when applying RES measures in a commercial setting with regards to willingness to adopt as well as in terms of financial investment in a novel technology.

3.6.2 Time varying discount rates

Discount rates greatly effect how individuals view an investment in Energy Efficiency (EE) as well as the implications of pricing increases. Experiments show that individuals use a higher discount rate over a longer time horizon than over a shorter time horizon (Thaler 1981; Benzion et al. 1989; Holcomb and Nelson 1992). Discounting in effect means that individuals view long-term consequences as less significant then short-term consequences. Behavioural economics aims to shift an individual from a shortsighted mentality to a farsighted one by moving away from immediate costs/benefits to both these occurring in the future. This idea of time varying discount rate alters our preferences, a simple example is the idea that most people would prefer R100 today versus R110 tomorrow, but most would reverse that decision if it were R100 in 30 days vs. R110 in 31 days. This means that an individual would prefer to not outlay now in anticipation of a greater future reward. Another aspect of discount rate is our ability to procrastinate and delay the inevitable. Given a choice between three hours of pain today or four hours of pain tomorrow, most delay for tomorrow. Extending that to three hours of pain in a month or four hours of pain in a month and a half, most would stick to a month, however when the day came most would again defer the pain to another day (O'Donoghue and Rabin 2000). This behavioural anomaly of procrastination does not go unnoticed to the individual and often they hold a value to the opportunity of commitment. This notion has been proven by Ashraf et al. (2006) where they show that people choose an illiquid asset over a liquid asset even if they have the same interest rate. The example used is that of people preferring a savings account with restrictions on drawing vs. that of freedom to withdraw, this had the side effect of increasing savings by 82% for those choosing the commitment based accounts.

A key point in this area of Behavioural model is the view that an individuals power must shift from "opting in" to the policy to "opting out", e.g. a form of commitment needs to be created that an individual can opt out of, not procrastinate about opting into. This takes advantage of cognitive dispositions of the individual.

3.6.3 Prospect theory and importance of reference points

Prospect theory is an important theory in enhancing the success of an energy policy. Traditional economic theory bases individual preferences on their individual wealth and on the price of a commodity, this being independent of the composition of their assets or consumption levels. Prospect theory states that welfare changes should be evaluated according to reference points, namely:

- Loss aversion;
- The reflection effect;
- Endowment effect;
- Status-Quo bias (Pollitt and Shaorshad, 2011).

Traditional economics has the assumption that individuals are either risk adverse or neutral, placing the same value on a loss as a gain. Prospect theory argues that valuation of losses is the mirror image of valuation of gains hence the term "*the reflection effect*". It states that decision making will exhibit the reflection effect when an individual is risk adverse in light of potential gain and in the collar ally, is risk seeking in the face of potential loss. The basic principle of this is the idea that individuals value losses higher then what they value gains and studies have proven that willingness to accept is higher then willingness to pay (Shogren and Taylor 2008). An example of this which Shefrin and Statman (1985) used the example of investors who often hang on too long to an underperforming stock due to a reluctance to sell at a loss, yet these same investors will quickly sell a performing stock that has gained in value. The next reference point is the endowment effect, which is a cognitive bias; this refers to the extra value individuals place on goods once their property right to have been established. In relatable terms this can be seen as motivation for small scale renewable projects, in that an individual will place a higher value on a system they own and hence will seek to maximize that assets vs. a renewable assets they contribute towards (in the form of increased tariffs etc.). The endowment effect is linked to the status quo bias view that individuals tend to stick to the default option chosen for them, i.e. presumed consent led to higher adoption rates then informed consent. This was demonstrated by Samuelson and Zeckhauser (1988) who showed how at Harvard university faculty, old faculty members were unwilling to change their healthcare plan having the option of a new one. Creating an environment where EE practices are the default option is a viable way of spurring investment in the sector. These behavioural differences need to be designed into a system or accounted for in an energy model if a great degree of outcome is wished to be obtained.

3.6.4 Bounded rationality

This is a phenomenon where individuals are rational; however exhibit cognitive restraints at processing information (Simon 1986) this has the effect in circumstances of creating deviations from the expected rational norm. Carrie Armel viewed Choice overload, heuristic decision-making and failure to asses statistical probability as three important manifestations of this phenomenon.

Choice overload: Refers to the difficulty in making a choice when there are too many available options. This can be viewed when attempting to negotiate the myriad options thrown at a novice investor in the Renewable sector. Simply, there are too many options, and this girth of options is hampering the ability for the individual to choose on their course of action. This effect also has influence in the supply and use of energy and will be discussed further in the proposed model.

Heuristics, decision-making and the failure to asses statistical probability are closely linked. The idea of Heuristics is of importance in explaining how we formulate our judgments and choices.

3.6.5 Heuristics

Heuristics are the short cuts we make in coming to a decision, our bias, or perceived knowledge alters our decision making process. In EE investments or system changes, how people assess the probability of an uncertain future event, namely energy price increases or shortfalls, along with the how they assess the future value of an uncertain quantity in the form of savings etc. alters the framework within which participation or commitment will occur. Individuals rely on a limited number of heuristic principles to reduce the complex decision making task of assessing probabilities. This method is useful, however it leads to systematic errors in decision-making due to its reliance on subjective assessments based on limited data validity. This reliance on subjective traits creates bias, which manifests itself in the intuitive judgment of probability.

3.6.6 Summation: Social Behavioural understanding

Clearly there are two distinct proponents to the model, in the form of a *social relationship* aspect and an economic aspect, hence the term *socio-economic system*. (This model does not exclude that of the technical, however the focus is on the socio-economic constraints within the three main sustainability constraints). Each proponent of the system needs to be discussed separately before being combined within the new model. The rational of this study, thus, has been the idea of changing the norm, moving away from neoclassical economic ideals to that of a *behavioural-based approach* places an increased focus on the initial assumptions of the model, particularly with regards to shifting focus towards psychological, sociological and institutional variables as being determinants of choice (Altman, 2006) This creates a certain degree of realism regarding an individuals simplifying assumptions in the decision making process. Further highlighting the idea that individuals incur self inflicted systematic biases and procedural errors as a result of the decision making process. In neoclassical terms this would imply that the individual has reoccurring irrationality as a consequence of these biases and their cognitive illusions. But why is this focused non-traditional approach viable when it comes to micro and macro economic outcomes?

Namely: Infrastructure plays a fundamental role through enabling and governing spatial flow of resources, goods and services (socio-technical system). There, however, still exists a need to understand how infrastructure systems develop and change within the wider economy, this development is emphasised by the socio-economic change exhibited. This focus on the interaction between infrastructure, economies and social paradigms creates a form of *co-evolution* within a complex adaptive socio economic system. This idea of co-evolution of systems within a complex setting highlights the key reasons for this non-traditional focus on decision making behavioural characteristics.

- Assumptions matter, not just for analysis but also for understanding why individuals behave how they do based on their cognitive abilities and environmental constraints.
- Cognitive capacity, cultural learning and the flow of information all have an affect on intelligent decision-making.
- Behavioural economic ideals, do not preclude neoclassical ideals, it merely enhances them.

Energy use is a form of consumption, representing not just a purchase of goods, but it defines even the time individuals invest in activities such as work, exercise, social media etc. This consumption produces a history, which has the attribute of maximising personal welfare. Hence, if consumption is too high or too low, how is an individual able to identify that? Thus maximisation requires knowing your current consumption rate as well as having the added ability of repeated choice.

Implementing behavioural models relies on understanding the problem of individuals who exhibit insufficient self-control, hyperbolic discounting as well as incorrect preference assumptions based on bias and illusions.

With utility occurring on an aggregate scale over time while choice occurs at a local scale occasion-occasion (Prelec, 2014) thus each choice an individual makes has a direct utility impact as a result of the consumption experience as well as an associated indirect utility effect on future consumption. Individuals often ignore this indirect utility leading to internality, this internality often leads to a consumption rate which when reflected upon is seen to be non optimal. This may seem trivial, however when the ignored indirect utility is in fact an externality then these ignored consequences now fall on other individuals. Hence the idea of consumptions and our actions related to consumption of energy and resources is vital in ensuring the true optimal outcome for not just the socio-economic environment but also the co-evolution of the socio-technical environment of infrastructure development.

3.7 Creating effective systems: The relationship between connectivity and behaviour

"*The lesson will always repeat itself, unless you see yourself as the problem, not others*"

– Shannon L. Alder

Arguably the greatest current and future challenge facing our society is the ability to achieve and maintain energy supply that is both sustainable and environmental friendly, one that is able to meet our ever-growing needs without compromising future generations the ability to meet theirs. If this is the greatest challenge, is the current approach towards addressing this challenge, one which focuses on how individuals need to become more sustainable with the aggregated affects of these actions sustainability, fundamentally an effective strategy in achieving overall grid and intergenerational sustainability? Perhaps it is better to focus on the sustainability of the system as a whole using individuals and their needs as the facilitator for effectiveness on a global macro level? The sub-optimation principle (Skyttner, 2001) implicitly states that if each subsystem were to operate with maximum efficiency, then as a result the system as a whole would cease to be maximally efficient and similarly if the system as a whole were to be maximally efficient then the subsystems would cease to be at a high level of efficiency. Interconnectedness relies on a balance between components, with an associated degree of reliance on the relationship between parts. Simply adopting Renewable energy technology, or being more energy efficient (when convenient) is not enough, in a systems setting this individuality is neither efficient nor effective and ironically perhaps has greater negative consequences from a systems perspective in that it fundamentally induces variability and weaknesses into the system that increase the potential negative consequences of external disturbances as a result of the system not being designed to withstand a perpetually stochastic environment. This chapter builds on the ideas and knowledge gained in the previous chapters. Using network principles it, looks at the *development of micro-grids* as the solution to individual and grid sustainability, moving energy production from a purely public good, to one where private individuals are able to cooperate under an environment of greater certainty, increasing their private good whilst increasing the overall public good as a consequence. At the end of the day, as Shannon Alder neatly highlights, *we are the problem*. Solutions need to start not with addressing the problems of society as a whole, but rather focus on the role of the individual within the collective and how solving our individual circumstances has the ability, when designed correctly, to aggregate into societal sustainability through an increasing level of sustainability in the energy grid itself.

3.7.1 "Not so smart" Electrical energy systems

Traditional energy systems consist of three main components (1) generation (2) transmission (3) distribution.

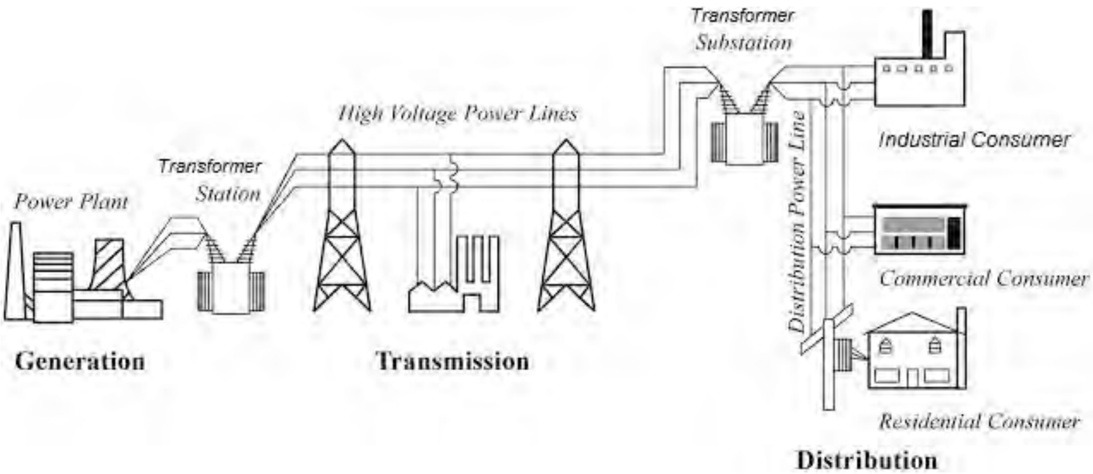

Figure 13: Large scale Grid network (oliver et al, 2015)

An in-depth understanding of the multifaceted components of the electric energy grid is beyond the scope of this paper, instead the focus is purely on the structure of the Low voltage (LV) grid system in relation to distributed generation and consumption in the form of Solar PV and battery storage and developing a two layered grid system consisting of the physical supply of electricity and the distribution of information. Understanding the theoretical weakness and vulnerabilities will enable a foundation for which future grid integration can be modelled on. Developing a two-layered grid system based on the physical supply of electricity and the parallel generation and distribution of information is critical for future grid sustainability. It must be noted that while this paper focuses on the LV grid in particular, the principles are scalable to the Medium Voltage (MV) and High Voltage (HV) grid with relative ease, however a focus on the MV and HV would take away from the potential existing within the everyday ordinary consumer currently overlooked.

When developing a viable solution to grid sustainability it is important to move away from the view of individuals agents being due a minimum service level in regards to energy supply, but to alter the view to those same individual agents being active participants and assets with n ability to contribute to the success of the grid system. This requires a market transformation, which challenged the hierarchal centralisation favoured for an alternative *hybrid decentralised and centralised modular system* using the power of the collective in an effective system setting.

3.7.2 Horizontal and vertical emergence

The structure of a complex system lays foundation to all collective activity in it. If agents accept the fact that the energy system at the macro level, and their own systems at the micro level for that matter, are highly complex, then is distributed energy production in the classical sense of decentralised islanded use, the saviour of sustainability we hope for? Is the increased drive to prevent localised failures creating an environment for increased failures at the global system scale? The following will be briefly use complex networks to illustrate theoretically why this sustainability agents aim for is a fallacy if they rely on the current grid structure when it comes to interconnectedness and communication among spatially segregated yet operationally connected agents under hierarchal control. This may seem paradoxical in light of the aims of developing an individual centric based model of an ideal agent in the grid, however it is the use of micro-grids and their properties, which merge the benefits of, distributed decentralisation with that of a centralised aggregated operation characteristics. It is the balance between order and the degree of disorder in a system, which alters effectiveness and it is this effectiveness which sustainability has the potential to emerge from.

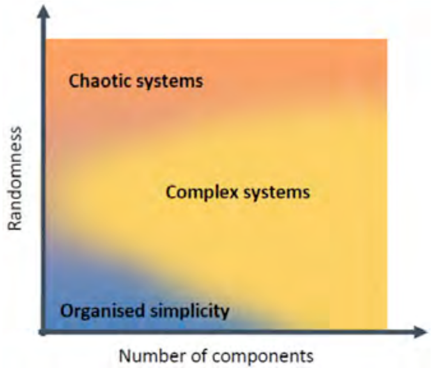

Figure 14: Balancing Order and disorder to facilitate ideal emergent phenomena

Focusing on network topology, in the energy system, defines how nodes are connected to each other, this definition crucially aids in determine the length in each step of power transmission corresponding to power consumption in the technical grid itself.

3.8 Literature on Microgrids

With the vast majority of South Africa's energy supply coming from centralised power stations with consumers interactions aligned to a central grid Micro-grids are discrete energy systems able to operate parallel with or independently from the main grid providing autonomous capabilities with the security of grid back up (General Microgrids, 2013). This autonomy is accomplished, but not reliant on, distributed energy resources (DER). DER are localised modular small-scale power sources which provide energy locally at the point of use, this includes; generation, storage and demand management (Electric power research Institute, 2014). This idea links directly with that of micro grid development and will be discussed later in the paper. The most common type of a micro grid is a "true" or "customer "Microgrid (µgrid) (Berkeley Lab, 2014). *µgrid's* are self governed and independently owned and maintained by a private entity of any size or scale. The municipalities responsibility ends at the Point of Common Coupling (PCC): from the PCC onwards an "*island*" effect is able to be created allowing those connected to the PCC to run independently from the grid, if so desired, as well as allowing no disruption to the grid or surrounding utility users in case of system failure. The definition of a Microgrid does not hint at a size prerequisite in order to be defined as a Microgrid, instead it highlights two key areas. The first being that is it a locally controlled load and that secondly it is able to act independently of the grid. These two characteristics of microgrids are convenient as they conform directly with, provided they are engineered to spec, Durban's current energy regulations and guidelines.

While this "*independence*" from the grid is not a fully achieved separation it has the effect of creating a platform for energy independence, along with grid interactivity and the potential for financial return in the form of buy back. This synchronicity, in light of ever increasing national energy shortfalls has great benefits in allowing a reciprocated approach to energy usage: i.e. grid draw when available and if needed and µgrid supply to the common grid in times of low grid reserves or shortfalls and when economic viability is exhibited. That relationship will be discussed in depth in following chapters as this key point has the greatest benefit in helping to alleviate South Africa's energy problems as well as smartening of the local energy grid. New forms of Microgrids are in development, *milligrids* (mgrids) (Berkeley Lab, 2014) are segments of the regular grid, which are setup to form Microgrids running concurrently with the main grid. This idea is very similar to µgrid's, with the difference being the regulatory and business models involved as they include traditional utility infrastructure. In the context of South Africa, and with rapidity of energy actions needed to be taken to address energy shortfalls, µgrid development will be the underlying focus of this research and of the chosen case study involving local factories in Durban. That decision was due to the regulatory, business, environmental and time viability of the establishment of a µgrid as well as the above µgrid adoption creates a platform for users to take control of energy production and supply, in essence allowing a previous end user to become a power producer, breaking the linear traditional energy model that exists in the country.

3.8.1 Microgrid, place in the system structure.

In the previous chapters reference was made the "appropriateness" of technology employed, this idea extends into this chapter and is constantly a guiding factor when outlining the potential role Microgrid development plays. The advantages of Microgrid development and in particular the development of µgrid's in Durban are significant, with a critical need for further examination and investment in the form of a real life scenario, through a case study. The current model of central power stations linked via transmission lines to the End Power User (**EPU**), cedes high levels of regulatory control over to a single entity with control over power production and distribution. This control has the antitheses of high levels of risk and responsibility. With the full reward comes the full acceptance of risk. Factors out of the EPU control and often in a far-flung geographic zone can have an effect on power supply. Micrograms have the potential to open up and broaden the current linear one-way model of power production, transmission and use, into a bi-directional interactive, dynamic energy system. Regulators develop and enhance power capacity based on financial returns and best practices for the business and for the country as a whole; µgrid's however have the key difference of being consumer driven in a more localised setting, Ceding some of the power and control over to the EPU, however this hand over of control comes with more responsibility for the user and a easing off of responsibility for the producer, in this case Eskom.

While the Idea of µgrid's has been around for a few years, the principles behind them are not often understood for the benefits they possess and hence their adoption and commercialisation has been curtailed through lack of under standing. The list of advantages is vast, as summarised as following:

- Improved energy efficiency;
- Minimisation of overall energy consumption;
- Reduced environmental impact;
- Improvement of reliability of supply;

- Network operational benefits which include, but are no limited to:
    - Loss reduction
    - Congestion relief
    - Voltage control
    - Security of supply
- Cost efficient infrastructure replacement;
- Balanced choices between investment and supply;
- Avoidance of large scale investment in energy production (municipal level);
- Economic benefits for the end user.

As µgrid's are determined, not by their size, but as a result of their function, advantages are applicable, irrelevant of scale. The case study involved a relatively small µgrid, which was developed and conceptualised with the primary focus on reduction of business-operating costs through lower energy bills, thus making the business more cost competitive in the current market place. This advantage was paramount in justifying the financial investment on the part of the business owner. However, through the course of the study it became evident that these advantages extended both ways, from the EPU to the municipality and as such when discussing the advantages of µgrid's it must be looked at from the eyes of both parties, the low voltage (LV) customer µgrid and the impact this µgrid has on the municipal medium voltage (MV) or High Voltage (HV) main grid operation, split up into three distinct categories:

- Category one: Financial
- Category two: Environmental
- Category three: Socio-technical

While all the categories are important, the financial aspect of µgrid introduction is viewed as being of crucial importance in the wide spread adoption of the principle and as such will be the focus of the following literature presented.

3.8.2 Financial Benefits of µgrid adoption, establishment of Place

In looking at the financial benefits to the EPU in a µgrid scenario, establishment of roles with in the µgrid needs to be clearly defined and understood. The distribution operator (DO) has a clearly defined role, that of the main supplier to the HV/MV grid, the next entity is the µgrid operator (µOP) who, while a consumer on the MV or HV network, may not necessarily be the net EPU downstream. The financial role of the µOP, vs. that of the EPU needs to be clearly defined in the project analysis phase. If the EPU is the µOP then this process is relatively simple and straightforward as direct benefit and financial reward along with risk is vested to a single entity. However, with further consumer coupling downstream of the PCC financial benefits diverge from a single entity to that of multiple entities with a stake in the µgrid.

These roles can become complicated and involve various legal and regulatory restrictions.

Step one: in gauging the financial benefits of µgrid adoption is the establishment of roles. Who are the DO, the µOP and the EPU?

This establishment of roles natural creates the second problem (step two) the problem of benefits and responsibility.

Step two: is the identification of benefit and responsibility within the µgrid.

Is the EPU to benefit financially from the µgrid or are they bystanders in the adoption of µgrid and benefit from greater power security while all financial benefits and risk fall solely on the µOP. The other obvious relationship is a sharing of benefit and responsibility, Financial responsibility and reward are shared by all downstream users from the PCC as well as the µOP, the µOP can be a private entity or a collection of EPU that have established a µOP.

There are three possible cases.

- Case one: Single µOP and EPU. I.e. µOP is the EPU and there are no other parties involved This basic case is easily financially and legally implemented and controlled with investment levels carried by the project initiator full financial benefit and responsibility is assumed by the single entity.

- Case two: Separate µOP and EPU with a direct relationship. This case revolves around the control of power supply and tariff structures downstream from the PCC by the µOP. The case study below is an example of this relationship where a building owner establishes a µgrid; sub metering the building tenants whom in turn, while not benefitting financially will gain through improved energy security.

- Case three: Separate µOP and EPU with an indirect relationship. This represents the amalgamation of separate EPU's via the establishment of a µgrid. With all EPU's forming the µOP and sharing the financial benefits and responsibilities. This case, while the most technically difficult to achieve does have vast potential in the current energy climate.

Once the establishment of roles along with benefit and responsibility is resolved the financial viability of the project can be gauged from the required perspective of the various entities involved.

3.8.3 Financial Benefits of µgrid adoption, identification of benefits

In neo-classical economic terms, supply and demand relates to an individual's rationality and his or her ability to maximise utility or profit (Investopidia, 2014). E. Roy Weintraub (1994) asserts that this thinking rests on three assumptions

- **Assumption one:** People have rational preferences between outcomes that can be identified and associated with values.
- **Assumption two:** Individuals maximize utility and firms maximize profit
- **Assumption Three:** People act independently on the basis of full and relevant information.

This way of thinking, and the above three assumptions, hold profoundly different meanings when it comes to the DO and the end user of that supply. The DO has the responsibility for a large zone of influence (in this case South Africa) while the µOP has the responsibility of a much smaller zone of influence of those down stream of the PCC. For this reason, the quantification of financial benefits needs to be separated and classified into the roles, which were established prior to the implementation of the µgrid.

In Case two: Separate µOP and EPU with a direct relationship the above three assumptions can be quantified into the three distinct roles based on there responsibility with regards to the µgrid.

	DO	µOP	

Assumption one	Preferred outcome of overall grid security and lower maintenance costs	Preferred outcome of energy independence and security from grid along with financial gain	Preferred outcome of energy security
Assumption Two	The maximization of grid efficiency with minimization of new investment cost for the country as whole	The individual and the firm are often one in the same, the minimization of pay back periods and capital gain is crucial	Security of energy supply leads to lower frequency of downtime in production due to grid inactivity
Assumption three	Energy planning and assumptions are based on the country as a whole and not on single entities.	Energy planning based on demand from those only connected to the PCC. Levels of investment can be directly correlated to that demand and benefit apportioned	A bystander in the process of energy planning prior to the µgrid, the EPU now plays a small role in the energy planning phase and who's demand directly effects the planning phase and operation of the µgrid

In neoclassical thought the quantification of financial benefit is easily determined through supply and demand. The demand for electricity leads to income derived from supply. The pursuit of efficiency and utility is the ultimate goal. Investment levels on capital expenditure are gauged via the level of supply able to be provided vs. the level of demand for the increased supply. This thought process has the simplistic view and the assumption that conditions will improve to a level of equilibrium in the long term without factoring in the consequences of the original disparity. In the case of the main DO, success is a relation of the demand as a whole and not as the sum of parts. Equilibrium is achieved through the reduction in supply across the entire grid, regardless of the disparity in demand between the various parts of the grid. Factors out of the EPU control, even if that EPU has taken steps to minimise their energy demand will still have an impact on the supply. A reduction in demand at their level does not lead to stabilisation in supply during times of shortfalls, preventing the ability of a return to equilibrium at downstream points of grid supply, relying on a return to equilibrium of the entirety of the grid.

This is where neoclassical economics fails. It does not have the ability of quantifying the financial losses associated with the non adoption of new often, non-essential technologies such as the µgrid and associated DER. µgrid and DER, have the potential of returning the system to equilibrium at the individual level (Supply meeting demand) Government investment and capital employed for these projects, needs to demonstrate tangible and real world benefits in order to help justify their use in the neoclassical sense, as well as providing a basis and a launching ground for future capital expenditure. However, this rating of the benefits to a socio economic system on purely classical neo-economic parameters often overlooks benefits in a dynamic societal sense, with regards to the financial effects and the potential human based consequences due to lack of investment in technology.

Neo-Schumpeterian economics is a branch in economic literature where the introduction of technologies and innovations in the technological fields is used in dynamic processes in order to drive qualitative transformations of economies, or in this case the energy grid. It views technological innovation as a driving force for greater development potential in socio economic systems. Technology and more specifically technological innovations are seen as a tangible parameter, not unlike the role pricing is seen to play in neoclassical economics. However unlike neoclassical economics where pricing is gauged through efficiency in a certain set of constraints in relation to supply and demand, neo-Schumpeterian economics deals with the consequences and potential effects on a socio economic systems through the removal of a constraint. This has a vast benefit if applied to µgrid and DER, moving investment away from broad generalist, state driven indicators into a more individual or local market, security and innovation driven ideal for indicator parameters. The establishment of the role of technologies to be used and the ability of future further innovations, along with the effects due to the removal of them helps to outline and quantify in real life terms, the effect of µgrid establishment in a localised socio- economic system and not just gauging the effects purely based on neoclassical economics on a broad basis. It allows a greater and far broader scope of understanding of a dynamic and evolving system. Providing a forward thinking approach to investment outcomes, neo-Schumpeterian ideals allow the effects of non-investment in a technology to be used and quantified in monetary and social terms in order to better gauge the benefits of an investment and possibly alter an investor's mind-set for the better.

This has the over riding effect of moving from quantifying the benefits of the µgrid in purely financial terms, to the quantification of benefit to the individual. This is difficult to gauge at the level of the main grid, however the level of a µgrid this effect is easily observed and quantified as illustrated below.

The country would be subjected to load shedding, this is reported to cost the South African economy X amount of Rands per year without reference to the effects on the individual. It is often reported that Y amount is needed over a period of n years in order to prevent these losses. It could be stated that the cost of Y is an additional X per year over that period thus raising the costs to achieve equilibrium from Y to (Y + (nX)). This broad scope of the problem is easily understood, in that the longer it takes to install the capacity the greater the costs involved in reaching that level of supply. In neoclassical terms this would be assumed as inefficiency on the part of business operation (South African economy) that will be absorbed through various mitigation measures, in Neo-Schumpeterian terms this is viewed as an expense on the business if not corrected and income if corrected. Allowing a platform for justification of capital outlay and the inclusion of these savings when calculating returns.

At the level of a µgrid this has even greater benefits. The individual is directly responsible for the profitability and success of the business entity. Meaning that the lack of investment in a technology to address supply or decrease demand is reflected through loss of income. During load shedding X is lost in production per hour n of downtime. Xn total losses for the duration of downtime. If no investment is made this value of Xn stays constant until the investment is made at grid level. If B is spent on DER, efficiency measures, demand reductions made etc. with a production of Z over the same n of downtime with a value of K Rands per Kwh of grid energy replaced. Then the value of losses due to downtime can be seen as having a total of (X-Z) n versus a constant value of Y without investment. A direct return over and above the value of energy produced can now be quantified and included in the investment calculation:

Without investment this non-capital outlay now becomes an added expense to the level of investment needed for energy security and should be added as an expense in the business

$$B_{\text{Capital expense}} + Xn_{\text{cost of non investment}}$$

With investment this capital outlay becomes an income generator, and should be used in calculating return on capital or reflected as an income in the business

$$B_{\text{Capital expense}} + Xn_{\text{cost of non investment}} - Zn_{\text{cost avoidance due to investment}} - K_{\text{value of energy produced.}}$$

In the framework of a µgrid this key differentiation in how we quantify the effects of disinvestment and how we look at justifying levels of investment will go a long way to the successful implementation and operation of Microgrids have the ability for reducing the responsibility of energy security and usage down to the individual. Reducing the responsibility on the state while increasing the responsibility and the control, which the individual has with regards to their own energy needs and security. This loosening of control and the separation of power from a totalitarian system of central production, control and supply does come with the question of security vs. risk of investment. Often a deciding factor in any business deal, the weighing of risk vs. reward (in his case energy security) is crucial to the level of commitment in the part of the EPU in a µgrid and will be discussed later in the dissertation.

3.8.4 Financial Benefits of µgrid adoption, establishment of an IPP

The establishment of a µgrid, regardless of the scale, has the over riding principle of identity creation. The production and supply of power is in the hand of a single state controlled utility (SU), with the exceptions of a few small, highly regulated power producers. This production and supply is closely monitored and guarded as it provides high levels of income for the utility and the relevant municipal distributors. This poses a myriad collection of legislation and technical requirements in order to co inhabit the supply and production space alongside Eskom. Along with a financial impact, Renewable projects alter demand forecasts for the state supplier and renewable projects in private hands without any state control or oversight are viewed as having the inherent risk of failure, due the compounded effect down the line when demand is suddenly unable to be met due to the factoring in of the failed renewable projects for production forecasts. These concerns and policies limit the commercial application of renewables to large scale secure projects which in turn reduces adoption of renewables to be solely for personal use with the commercial potential extending only so far as consumption reduction on a segregated individual level. This has the effect of reducing a potential small-scale power producer to the level of a consumer with the same rights, responsibility and role in terms of grid interaction. This classification exhibits inherent shortfalls outlined below…

- Decentralisation of renewable technology
- Inefficient use of small scale renewables to address peak demand shortfalls
- Lack of customer-to-grid interaction to combat energy issues
- Restriction of access to financial incentives due to scale
- Monopolisation of energy production and supply
- Failure to fully utilise existing infrastructure, thus increasing costs involved
- Lack of incentive for a municipal level of investment in mitigation efforts through renewable adoption

The current model of energy supply and demand prefers a “good citizen” to an “ideal citizen” Soshinskaya, Crijns-Graus, Guerrero, & Vasquez, (2014) define Good citizen as the traditional model of user, who can import but not export active power which leads to income generation from energy and associated use of system costs (UoS) while defining an “*ideal citizen*”, as an active participant in the common grid through the buying and selling of active and reactive powers. Energy supply, along with the relevant UoS charges account for around 15% of EThekwini’s GDP according to Colin Openshaw the regional IDM manager for Eskom, With an associated revenue loss of between 8 – 10% as a consequence of renewable adoption currently. This loss however does not factor in the potential associated with higher grid security for the individual as well as the municipality, as will be discussed further.

3.8.5 Role and scope of Eskom in the supply of energy

Eskom was established in South Africa circa 1923, becoming a wholly state owned and controlled company in 2002 through the conversion to a public limited liability company. According to Eskom (2014):

Eskom is one of the top 20 utilities in the world by generation capacity (net maximum self-generated capacity: 41 194MW). The State Utility (SU) generates approximately 95% of the electricity used in South Africa and approximately 45% of the electricity used in Africa. With the further 5% of local production generated through non- utility generation (NUG) The SU directly provides electricity to about 45% of all end-users in South Africa. The other 55% is resold by further redistributors (including municipalities) who will charge a slightly higher rate in order to generate revenue for the local GDP. The SU has committed to an extensive capital expenditure programme in order to address the energy shortfalls that previous lack of planning has compounded. This severe energy shortfall means that drastic measures have been taken, with the aim of mitigating the effects of the crisis. This has led to the re-commissioning of currently de-commissioned coal-fired power plants as well as the construction of the new Medupi and Kusile coal-fired power stations, two new gas-turbine plants, and the Ingula pumped storage plant. While able to address current energy shortfalls this reliance on fossil fuelled based power production will increase future risk exposure to planned environmental emission restrictions and dwindling fossil fuel supplies. And with only 5% of the countries energy being currently produced via NUG means this insecurity on the part of the SU in effect becomes the insecurity of the country and it’s inhabitants as a whole who, due to regulatory restrictions, currently have the ability to offset a part or the entirety of their own energy use (at a small scale) without having the ability to take the next step and actively participate in the energy market the adoption and expansion of Microgrid activities will enable the consumer to take that next step, assuming a degree of responsibility for energy production and distribution in south Africa, turning a previous user and non- contributor into an IPP, combine many thousands of these small scale IPP and microgrids, and the ability of the collective will be able to affect wholesale change at a level far greater then that of the individual. The reliance on the SU shifts towards self-reliance and wealth creation.

3.9 Microgrid case study in context

When finding a comparable case study with which to compare the relevance of the research into the application of microgrids in Ethekwini, it is important to compare and analyse similar topography and geographical characteristics with regards to a broader case study. A case study of an isolated autonomous or a semi autonomous Microgrid, is in fact, not comparable to the research scenario of a weakly connected Microgrid as is the foundation of this research. In general weakly connected implies the integration of the Microgrid into the broader energy system with the ability to separate from the system when desired. This is in stark contract to isolated and semi autonomous where the microgrids can be seen as a separate system entirely from the broader energy system and thus effective integration of the energy system is not the over riding aim. This section will, focus on a local and international comparable and the benefits and limitations experienced in each case.

3.9.1 Local case study: Durban ICC

The Durban ICC is a 33 000 m2 event space, currently with a redundant 11Kv supply with four 1MW backup diesel generators and an 180KW UPS. A recent study by the DER-CAM, grid integration group at Berkeley modelled a 2022 theoretical Microgrid set up for the ICC in order to evaluate to evaluate the potential in the building. The study moved away from a focus on the technical to the purely economical factor of whether the building could potentially financially benefit in the long run from Microgrid adoption along with the associated green technologies.

Findings

The study assumed a 60% decrease by 2020 in the cost of storage systems as well as an increase in the efficiency of solar PV modules to around 30% (Goldman Sachs) The study predicts a 12% annual decrease in the energy costs when compared to a traditional grid system. More important that the potential savings was when the questioned was asked if it was possible for the building to function as a stand-alone autonomous system. It was found that with the available roof space and the prohibitive costs of technology meant this was impossibility. This however did not prevent the study from finding alternate benefits for the adoption.

As a connected component of the grid system, how the Microgrid reacts to system pressures is just as important as how it contributes to those system pressures. The figure below highlights the potential contribution microgrids have for the macro energy system with the adoption of renewable technology

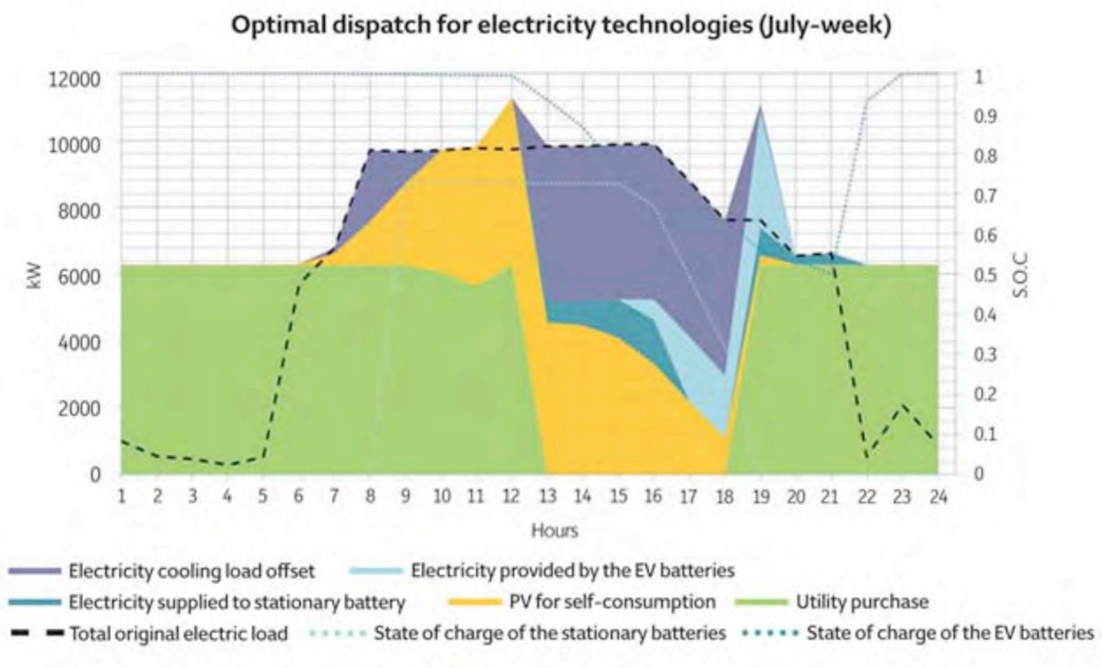

Figure 15: Durban ICC load profile model

This illustrates the load shifting inherent in the proposed systems as well as the ideal "grid behaviour" of the Microgrid. In essence the system contributes beyond generation in that its footprint on the grid system is reduced through load levelling of its demand to a more predictable profile while shifting some of the load to off peak periods when system demand is lower. The study also highlighted the need for a storage system capable of increasing the ability to meet the buildings demand. The study proposed the partial fulfilment of this through the use of Electric Vehicles (EV) as a form of mobile storage. Having the ability to contribute some of their stored energy to the building before recharging in off-peak periods. This concept may seem radical, however the basis is in the need for a social conscious with regards to our energy environment. The investigation in later chapters discusses this possibility, however the reliance is not on the use of EV and focuses instead on aligning buildings for optimal energy sharing and use.

Conclusion

The investigation into the establishment of the Durban ICC as a Microgrid by 2022 highlights the latent potential in focusing on building's as producers and stores of energy for the grid. The study did highlight the greatest threat to making microgrids economically viable, namely the reliance on feed in tariffs. This reliance assumes a demand for the energy produced which is not always the fundamental case. Thus the case study stressed the importance in the use of a viable storage system able to compensate for that reliance on volatile demand for the energy.

3.9.2 International case study: Santa Rita jail California

The Santa Rita jail is arguably the best example of a commercial Microgrid today. The jail has a diverse mix of DER technology able to meet and exceed its peak demand requirements as well as having the ability to operate on islanding mode when the redundant supply experiences difficulties. Of fundamental importance for this case study is its ability to act as an example of a self controlled entity or system when aligned with the macro grid as a whole. Simultaneously from a utility perspective the Microgrid is indistinguishable from other users/ facilities that do not incorporate DER's into their energy mix. It's this characteristic which is pivotal in ensuring the Microgrid operates as a component of the macro energy system and not as a standalone individually identifiable system which is not an integrated component of the system as a whole.

Components of the Current DER system

The Santa Rita case study incorporates many differing technologies; some green while others are more traditionally, this however is coupled with a storage system able to harness the intermittent produced power in times of excess supply. The DER systems consists of:

- 1.2 MW Solar PV system
- 1 MW fuel cell for hot water heating and space heating
- Five, 2.3KW wind turbines

- Two 1.2MW emergency back up diesel generators

Current system shortfalls

The previous non-Microgrid system experienced multiple shortcomings, namely with regards to system susceptibility to grid conditions as well as internal conflicts between the diverse mix of technologies. The system also lacked the ability to contribute to grid supply in times of over supply in the renewable systems. The DER systems were found to not contribute significantly and consistently to reducing peak demand load, this is due to the interconnection requirements of the local energy provider which has a requirement that the DER system discounting production when grid supply is interrupted. This requirement with regards to supply interruption is not down to full-scale loss of supply but voltage and harmonic interruptions as well. THs severely impacts on the fuel cell, which requires 18 hours to reach full capacity again. While the fuel cell system is down the intermittent nature of the PV system doe to climatic conditions is not able to contribute consistently to a reduction in peak demand when applied as a stand-alone system.

Further more the reliance on diesel generators for critical back up loads increased the environmental footprint of the project. Beyond the environmental though, the operation of the diesel generators prohibits the use of the other DER as a result of the disrupted harmonic and voltage characteristics of diesel generator production. This severely limits the entre systems ability to meet demand requirements in times of grid down time. This scenario is also further exasperated by the central control system tasked to handle a complex system of interconnected individual DER systems. Opening up the system to down time as a result of a single mistake or error with a single component of the system.

Additional systems added

- Four 500 KW battery storage systems
- Advanced communication system
- Establishment of a Microgrid

The Microgrid system is outlined in figure 16 below

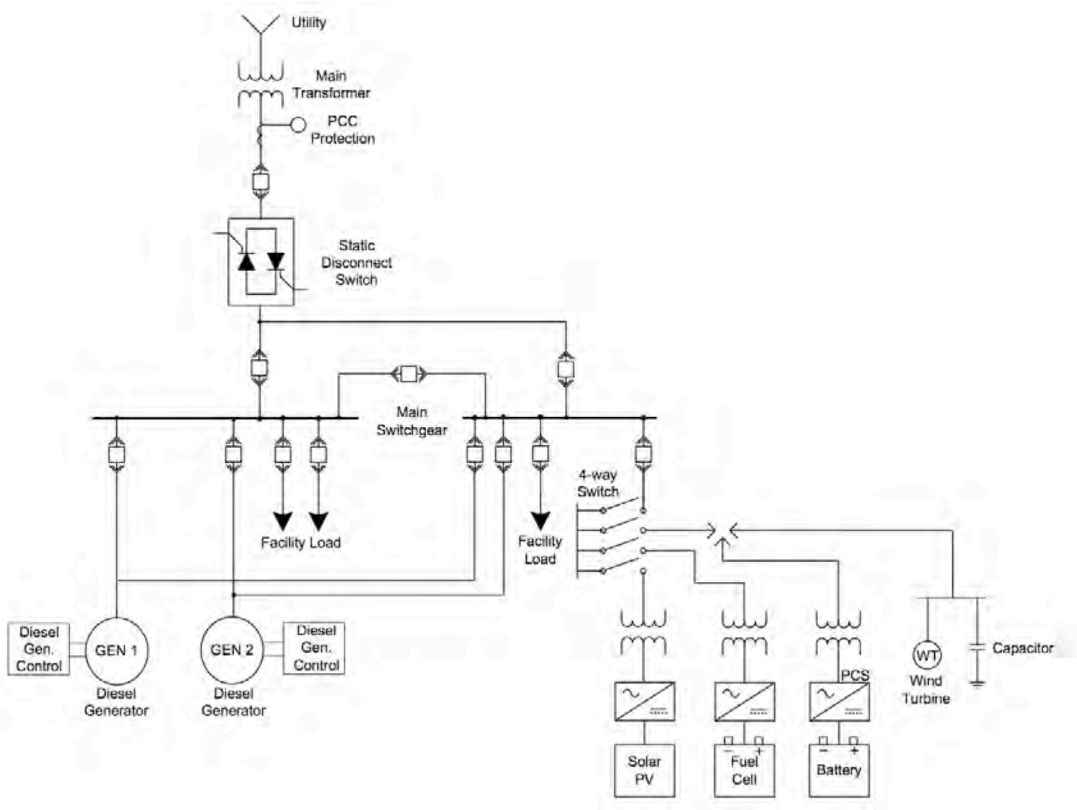

Figure 16: System structure (Chevron energy systems, 2015)

The main component of the systems success is the 2-MW, 4-MWh Lithium Iron Phosphate battery system which facilitated energy arbitrage as well as assisted with the smoothing out of load frequencies allowing all systems to run in parallel.

System results

The system exceeded all required objectives with results such as

- A 95% offset in the peak power load
- A 98% energy consumption offset for the peak period noon to 6PM

- A 15% reduction in peak load from incoming feeder

Establishing a Microgrid enabled the existing DER and the added systems to function at an optimal, providing substantial load enhancement as well as a reduction in overall facility demand. Allowing the DER systems to function at an optimal level as well as having the ability to store and distribute energy as required opened up further avenues for future distribution and energy use.

Chapter Four: Methodology

The purpose of this research is primarily with regard to the potential inherent in individual energy consumers connected via common grid infrastructure. This paper is broken up into two primary areas of focus, *Area I* being the quantitative analysis of a single individual consumer while *Area II* is the theoretical investigation of a collection of similar users based on the results from focus *Area I* and the literature from the preceding chapters to form a foundation for promoting a more integrated and distributed energy system to achieve sustainability, driven by individual agents and not purely centralised means. The purpose of this chapter is to (1) Company profile and rationale for investigation (2) Describe the research methodology of this study (3) Instrumentation and data collection practices (3) Limitations and uncertainties of the study

4.1 Company profile and rationale

Ocean Blue Silkscreen Printers produce screen-prints on textiles since 1993. Nearly 900 000 screen-prints are produced each month. Ocean Blue has 10 automated screen-printing machines. Ocean Blue is one of the three largest textile screen-printing company in South Africa. They run ten fully automated state of the art printing machines together with five curing ovens. The factory runs 24 hours a day Monday to Friday morning then closes Friday lunchtime. Depending on workflow Friday night, Saturday day and Sunday nights are often worked to meet production demand. Ocean Blue Silkscreen Printers employs 107 staff. Their energy cost is approximately R2M per annum, made up of purchased electricity from eThekwini municipality. They occupy 4000m2 occupied by plant and buildings. The annual turnover is around R25Million. Ocean Blue does both clothing textile prints, which can be found in many stores including Woolworths, Edcon, Ackermans and Mr Price. Ocean Blue also does promotion printing and in the past have done jobs for SABS, Famous Brands, ECR big walk and many more.

In light of the current and future economic environment, cost cutting in every avenue needed to be investigated. With energy costs already accounting for almost 10% of the annual turnover, any further increases have the ability to severely reduce income. The company's reliance of its energy supply means that the business is highly susceptible to outages costing the business R3000/hour in expenses due to downtime. This coupled with the increasing cost of electricity provided the rationale for the study from a building owners perspective.

4.2 Research methodology

Due to the nature of the research a theoretical qualitative study of buildings energy use was undertaken, based on collected data facilitated as a result of an energy audit on the building. Choosing to use a more qualitative and theoretical approach to analysing the buildings energy characteristics and place in the macro grid, allowed for a more abstract irrational approach to identifying the possibilities inherent within the structures of a Microgrid. The research developed in the following stages

Stage one: Developing a rationale for the adoption of a DER system and Microgrid

The first section relies on municipal supplied energy use data for the macro system as a whole, as well as high lighting the current energy climate it also serves to form a foundation for the justification of an energy arbitrage strategy. Justification for the use and inclusion of this data in the study is down to the notion that the data is municipal supplied and is the same data to which the energy provider gauges the current status of the energy climate with regards to load profile characteristics. The data also shapes the way consumers view energy use and the economic cost and system constraints present

Stage Two: Energy Audit

A practical and quantitative portion of the study, the collection of usage data was employed to develop an average load profile of the building. Namely with regards to,

- Consumption levels;
- Consumptions patterns.

> This quantitative aspect is required in order to develop a picture of the current status of the building's energy use in order to distinguish the weak characteristics of the buildings load profile. This will allow the identification of the most pertinent areas for address.

Stage three: Renewable retrofit strategy

Stage three's objective is quantifying the distributed potential existing for the specific case study site, as well as understanding the best method of renewable energy use for a business, who's primary focus is not altruistically based on a decreased environmental footprint but more on the economical performance of the system. The investigation of the renewable system was based around the following points

1. Identification of a Viable technology
2. Production potential of chosen renewable;

3. Various Scenarios for more effective use of the renewable production;

4. Economic vs. environmental discussion.

The data was derived from a solar study performed by Art Solar at the site using relevant industry standards and assumptions. Due to the vast quantities of data available on solar potentials in Durban, the use of average yearly data is sufficient to give a detailed average on the feasibility of a solar PV system

Stage four: Microgrid development

Stage fours objectives is understand the role microgrids can play as well as identifying the barriers to Microgrid development in order to deeper understand the consequences and possibility existing in their establishment. This relied on a theoretical desktop study drawing data from the literature review as well as case studies presented in chapter 3

- Understanding the process of adoption and associated constraints;
- Economic reasons for adoption: Consumer;
- Consequences of large-scale adoption of Microgrids.

Stage five: Willingness to invest

Stage five's objectives are purely the development of a deeper under standing on the potential role a consumer could play in a more distributed grid. Identifying the barriers to adoptions as well as the levels of assumed risk a consumer is potentially willing to accrue with regards to an enhanced and more sustainable grid. This stage of the research is largely a subjective observation with its roots in the preceding literature as well as personal observations during the research

- Understand what drives the consumer to invest in renewables;
- Identifying the degree of responsibility a consumer would assume in terms of their energy production;
- Identify ways in which the consumer feels more secure in investing in sustainable measures.

4.3 Instrumentation and data collection methods

The research fundamentally has a reliance on being a predominantly desktop study, attempting to draw a link between theoretical and real life subjective application. There was however a portion of the research, which relied on data collection, primarily with regards to the energy use of the building. This was conducted in the form of an energy audit

Data collection was facilitated through the use of a power quality meter, in this case the A-Eberle PQ Box 100. The meter was installed for a period of 14 days. This data provided an average load profile for the building as well a various harmonic and voltage curves which provided an insight into the quality of power supplied.

The meter was serviced within the required time frames.

Beyond the quantitative collection of data through the use of a power quality meter, the use of first hand observations was employed in order to investigate the suitability and correct procedure towards applying the best DER system in light of the building requirements as well as financial restrictions.

4.4 Limitations and uncertainties

At the level of this study and with available resources, there were several limitations inherent in the research. A data collection period of only 14 days is enough to draw an idea of the energy environment and requirements of the building. It however lacks in providing an in-depth and clear picture of the buildings response to environmental conditions as well as internal changes. Due to the cost of the equipment involved it was not possible to meter each individual machine, instead the meter was applied to the main incoming feed. This gave a picture of the factory as a whole and did not allow for an accurate survey to be conducted on each individual machines requirements Often general weaknesses or traits in a buildings load profile are not due to every machine or component equally, but one or two parts of the system which are not functioning optimally, and as such applying a blanketed recommendation can often have negative consequences as those components originally operating optimally now will find themselves being negatively altered.

Another limitation involved the use of subjective observations and theoretical discussions on the potential for the systems. Due to the limited time frame, as well as the limited available resources for the physical installation of the systems, Reliance was placed on finding conclusions and potential from relevant literature, supplied data, observed data as well as personal experience. While this is a weakness of the methodology employed, the use of sound justifications is enough to afford the observations merit in the context of the paper.

This reliance on subjective observations, manufacturer supplied data as well as desk top study data meant that uncertainties are introduced with regards to the validity of the data provided. These uncertainties were a cause for concern, however the potential for negative consequences of inaccurate data was mitigated through the verification of research data through accurate references as well as personal expertise and first hand knowledge.

4.5 Summary of methodology

Fundamentally being a desktop study, this research relies on sound conclusions being drawn from available literature and first hand observations. Validity is provided through the justification of decisions as a result of sound conclusions and references backed by published data relevant to the field of study. Limitations and uncertainties, while present and acknowledged are again restricted as a result of referenced justifications as a result of an in-depth desktop study, prior to the commencement of the research.

Chapter five: Investigation of one system making a difference: The evolution of the Durban power grid

"When Simplicity is broken up, it is made into instruments. Evolved individuals, who employ them, are made into leaders. In this way, the Great System is united."

- Lao Tzu

The Tao Te Ching (Verse 28)

Green technology, Renewable energy, and efficiency measures, among others, currently represent the greatest, and perhaps the only answer to bringing societies ever-increasing energy requirements in line with the earth's carrying capacity. Part of a solution that is hoped to prevent Hardins "tragedy of the commons" If individuals were to rely purely on the traditional classical approach of analysis, based on promoting and guiding their isolated actions within the confines of a competitive environment then perhaps an every increasing adoption rate of renewables, green technology and efficiency measure is in fact not the solution able to achieve sustainability. Arguing for this case becomes apparent when using a systems approach, becoming increasingly clear, that in this solution we hinge our hopes on lays our greatest and most immediate, challenge for our current energy system. Why is this so? Surely any measure optimal then the norm is good? `The answer is rather paradoxical; being ever more efficient allows individuals to use more, thus in effect efficiencies antithesis is the ability to consume more. This ability when paired with a system not designed with an ability to adjust to variability provides arguably the greatest stimulus to increasing resource use and failure of sustainability objectives as well as decreasing levels of system robustness. As previously discussed it is not efficiency, alone which will achieve sustainability. Sustainability relies on not just individuals actors within a system being more efficient, instead it relies on the system as a unit being more effective. Skytnner's sub-optimisation principle (Gharajedaghi, 2006) highlighted the interconnected nature of systems, where there is a fine line between what betters the part and that, which betters the whole.

This case study builds on the previous chapters and seeks to answer the fundamental question of weather by taking an individual centric approach in the form of modularity of individual consumers, we can as a result aggregate influence on the operation of the energy system so as to better fulfil the initial aims for which the system was created, that of providing energy to all parts of the systems in a sustainable manner. It is hoped to question weather sustainability as a characteristic, not an outcome, can emerge from the system and if so, how can this emergence continually tend towards sustainability for generations to come even when placed under stress by external and internal variations. Introducing distributed energy sources is vital in ensuring system robustness in the long term, however this introduces variations into the system which previously were not designed for, and if left unchecked has the ability to reduce overall effectiveness of the system as a whole even in light of a scenario where individual agents become increasingly more efficient and sustainable. No longer can individuals be able to exist in isolation, their daily lives and their existence is a function of the immediate actions and their environment, primarily consisting of those we are connected to, known and unknown, these relationships within a system hold the key to creating an adaptive effective system, able to harness individuals increasing efficiency and as a consequence allow sustainability to emerge. The very definition of complexity hinges around the whole resisting reductionism in that its parts are unable to be studied in isolation. For the sake of this case study the focus will be on how it is possible to quantifiably facilitate and integrate individual actors within the system so as to induce complex properties and adaptions. Using Agent based modelling principles and theory from previous chapters it is hoped that a discussion on what is possible will stimulate thought on the current system. An in-depth generation of a working model is beyond the scope of this research, however this study will serve as a stepping point to further studies and discussion on more in-depth real world complex scenarios. In Systems theory the patchiness principle refers to the notion that system instability is as a result of a systematic lack of capacity to use a variety of resources. The current rigidly centralised hierarchal system is that inability the patchiness principle refers to, as Richardson's (2005) neatly sums up " … to maintain a level of stability in the face of changing conditions a system should not invest too much time and effort into one particular way of doing things. A capacity to take advantage of a plurality of resources allows the system to 'move with the times". An individuals inability to transition from their current mind-set of being purely energy consumers with a right to energy, to that of being active participants in the supply or prosumers will inhibit transition to a grid structure which is more resilient to negative events and will fundamentally inhabit the effectiveness of renewable energy production and as a consequence the achievement of a sustainability in the long run.

Investigation Part I: Microgrid development, creating sustainable agents

5.1 Introduction

A constant theme of debate thus far has been the difference between a system which coverts efficiency and that which favour effectiveness, for the sake of Part I of the investigation case study it is pertinent to side-line Skytnner's Sub-optimation principle on the interconnected nature of a system, and focus simply on an individual agent within the system in order to derive a theoretical best case scenario for an individual agent, in the current energy climate and grid structure. Simplifying the focus from the complex aggregated system level, to a micro individualistic one is favourable in abstracting the building blocks of the electrical system, namely that of the users. This approach, however, lacks when abstracted to the macro level of the system itself, where the individuals are replicated into a population of users which intuitively will not in reality be heterogeneous in consumptions and production, and which if attempted will exhibit high degrees of complexity beyond the scope of this paper. This section will merely serve to show the potential of one particular agent, and will serve as a discussion on how this impacts sustainability for Durban at grid level. This chapter is in line with the current drive for consumers adopting renewable technology and alongside that become more efficient, and will highlight the strengths and weaknesses of this individualistic approach particularly highlighting the latent potential which exists if individual agents are empowered to play a direct role in the sustainability of Durban’s energy supply. This section of the investigation embraces the patchiness principle in attempting to increase our capacity to use a variety of resources within the energy environment, achieving that I’ll show starts with a focus on an individual user.

5.2 The case study: Evolving resource variety through Individual users

The case study revolved around a medium enterprise (< 200 employees) that is classed by eThekwini Municipality as a business electricity use consumer. This case study agent will be assumed to represent all agents in the grid (regardless of real world use characteristics) who fall under the medium enterprise guidelines. This is able then to represent the possibilities inherent within the existing consumers in line with their needs and aims for energy use. Stage one’s energy audit provides a platform for understanding how the building uses energy as well as providing a picture for the current and future usage demands.

5.2.1 EThekwini electricity stats: Bulk energy users summary of reasoning

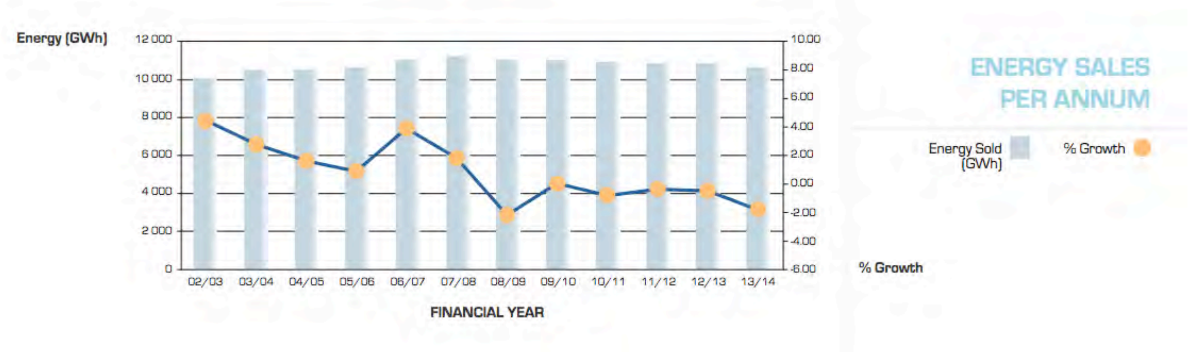

Figure 15: Energy sales per annum (EThekwini electricity, 2014)

Figure 16: Growth of bulk Customers (EThekwini electricity, 2014)

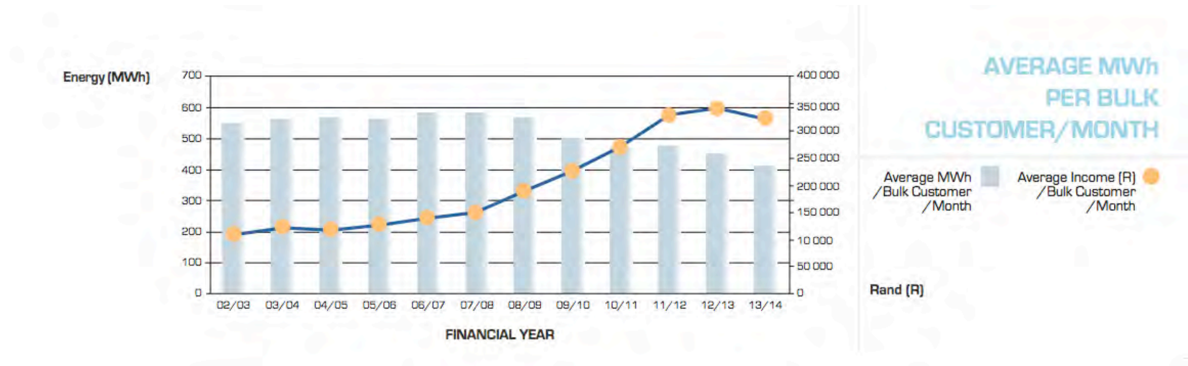

Figure 17: Average MWh/ bulk customer/month (EThekwini electricity, 2014)

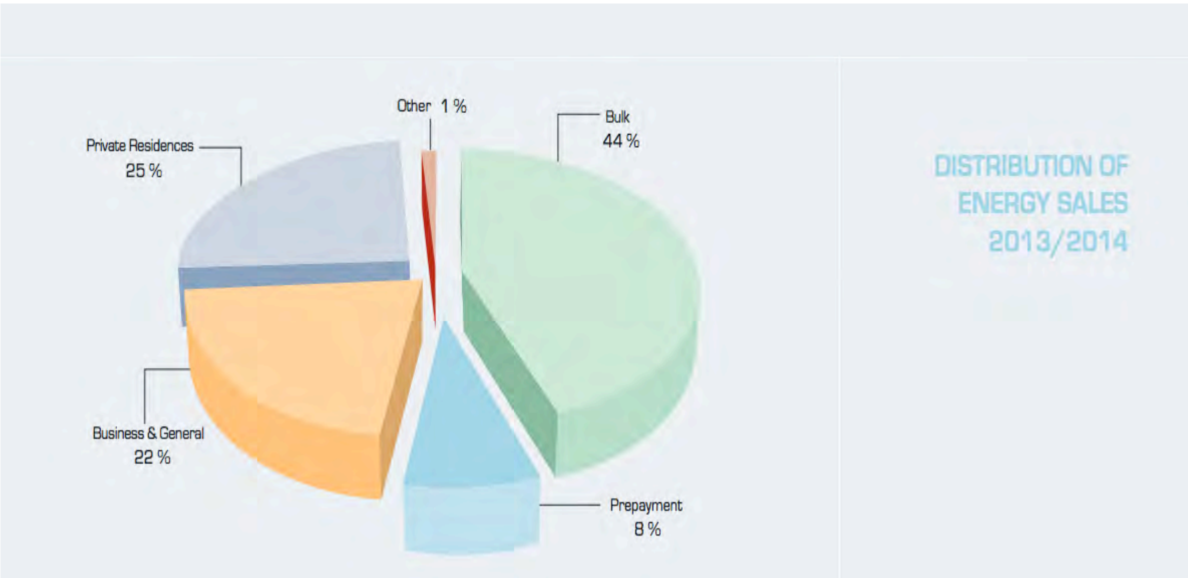

Figure 18: Distribution of energy sales (EThekwini electricity, 2014)

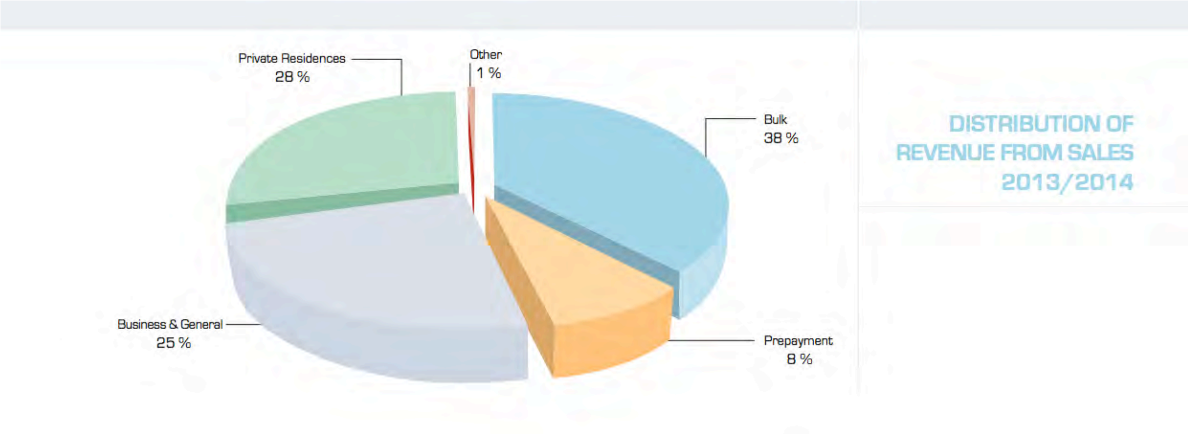

Figure 19: Distribution of revenue from sales (EThekwini electricity, 2014)

From the data supplied in EThekwini's electricity's annual report there are a number of apparent observations:

1. Energy sales across the board are decreasing yearly, whilst there is an increase in bulk customers;
2. Average MWh/ bulk customer is decreasing (partly accounting for the decreasing sales);
3. Bulk customer's account for 44% of distributed energy capacity, while revenue from bulk consumers only accounts for 38% of generated revenue.

The data in the report shows a disproportionate correlation between the capacity supplied to bulk consumers and the income generated. Is this a sustainable relationship? The simple answer is no. As part of the municipal climate protection programme, the Durban climate change strategy (DCCS) sets out a target for 40% renewable production by 2030. If the largest sector supplied energy is benefitting from lower energy rates, whilst the payback periods for renewable energy technology is not feasible, even if one where to include the proposed power purchase agreements. It becomes evident that a target of 40% by 2030 is not achievable if there is not a concentrated focus on expanding the methodology when it comes to renewable adoption and resource allocation for a number of reasons.

Reason one: From a municipal view point, promoting renewable adoption in the residential or Business and general (B&G) tariff users, will lead to a loss in revenues exasperated by the cost of purchasing the excess power produced and then supplied to the bulk sector. This has further knock on effects with regards to system maintenance and expansion.

Reason two: From a bulk consumer perspective, large payback periods, coupled with relatively affordable energy supply and lack of security of investment in renewables, means that there is no urgency for adoption or incentive to head sustainability calls for reasons other then pure altruism or environmental concern.

For these two reasons It is believed that if the municipality were to place their entire focus on the almost one million bulk customers they would achieve their objective of 40% renewable adoption along with increasing their revenue through freeing up supply and funds to expand energy supply to more profitable sectors such as the residential market and the ever increasing lower income household energy demand. The following investigation of a single bulk consumer will focus on critical areas, namely:

4. Peak Demand reduction
5. Energy security
6. Environmental benefits
7. Resource potential

Changing the method used to view energy consumers (in this case the bulk consumer) and instead seeing the user, as a resource will allow EThekwini Municipality to meet environmental targets as well as renewable targets. Increasing grid security, system robustness and system variety, without having an effect on revenue and electricity services to other sectors.

5.3 Stage one: energy audit

In light of current shortfalls there is a need for peak demand reduction, this section highlights the potential in a single consumer at meeting those primary needs of sustainability as well as the secondary economic sustainability of the system as a whole

5.3.1 Usage patterns

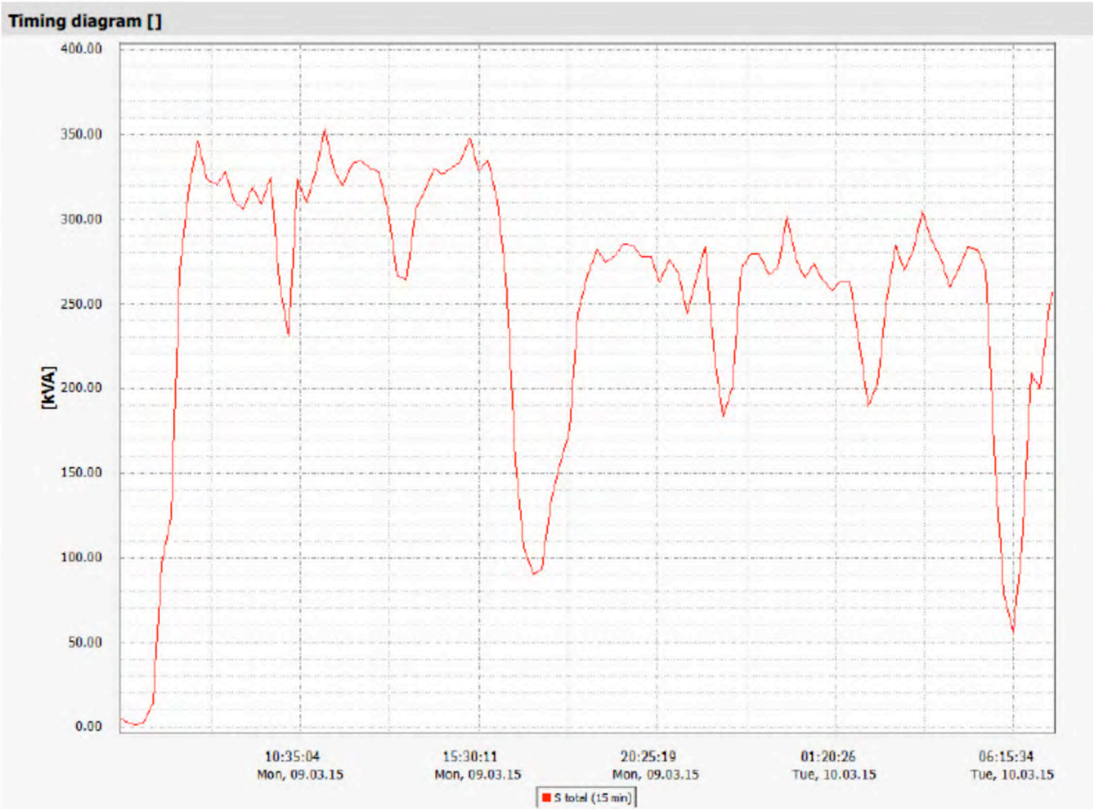

Figure 20: Typical load profile for case study building

Through an energy audit figure 20 was generated representing a typical daily load profile for the case study building.

Will the profile itself is not uniform; there is a repetitive pattern of peaks and crests.

Peak periods: Between 7:00 and 15:00 max Demand of 355kVA with a lower peak of 300kVA between 18:00 and 6:00

This in comparison to figure 21 of a typical load profile for a mixed-use building from a previous case study with a continuous uniform single peak

Peak periods: Between 7:00 and 17:00

The common factor between both the case study building and previous data is the low levels of off-peak power use and the high demand during the peak hours when the energy grid is operating at near capacity.

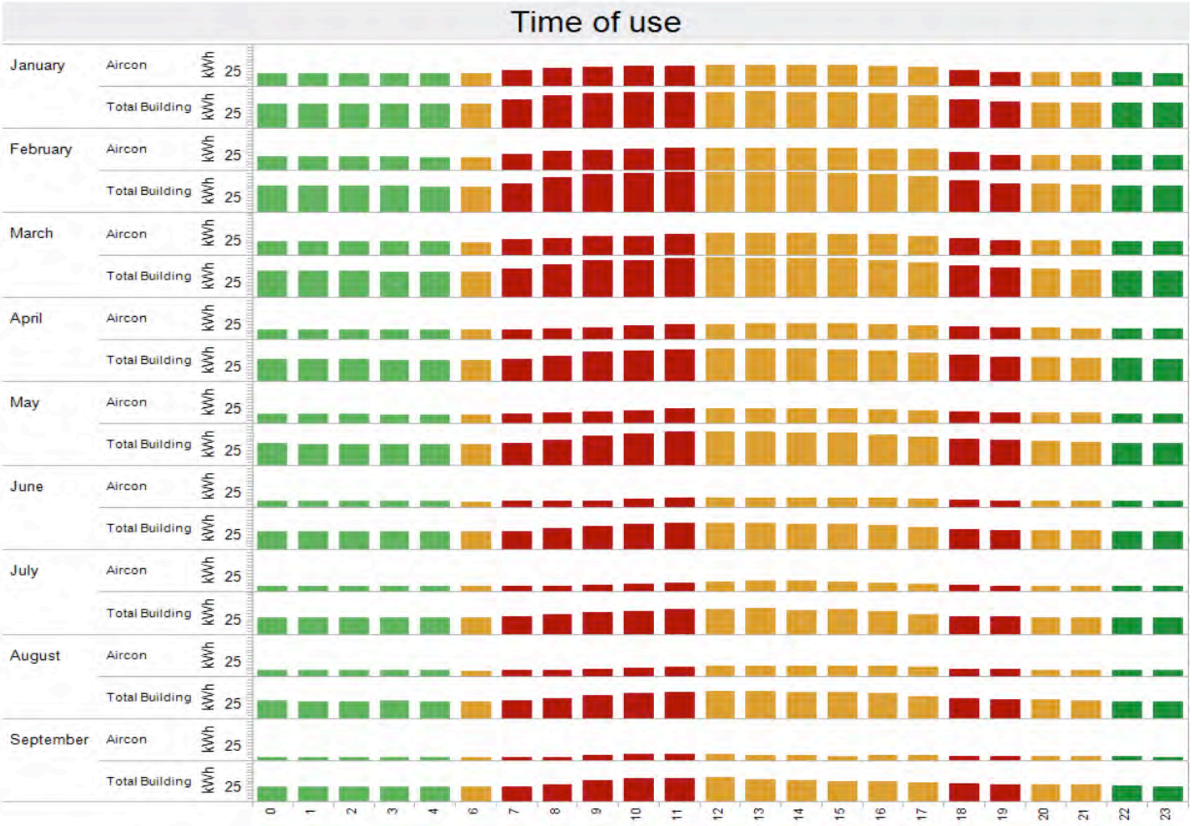

Figure 21: Load profile for a sample mixed-use building bulk user

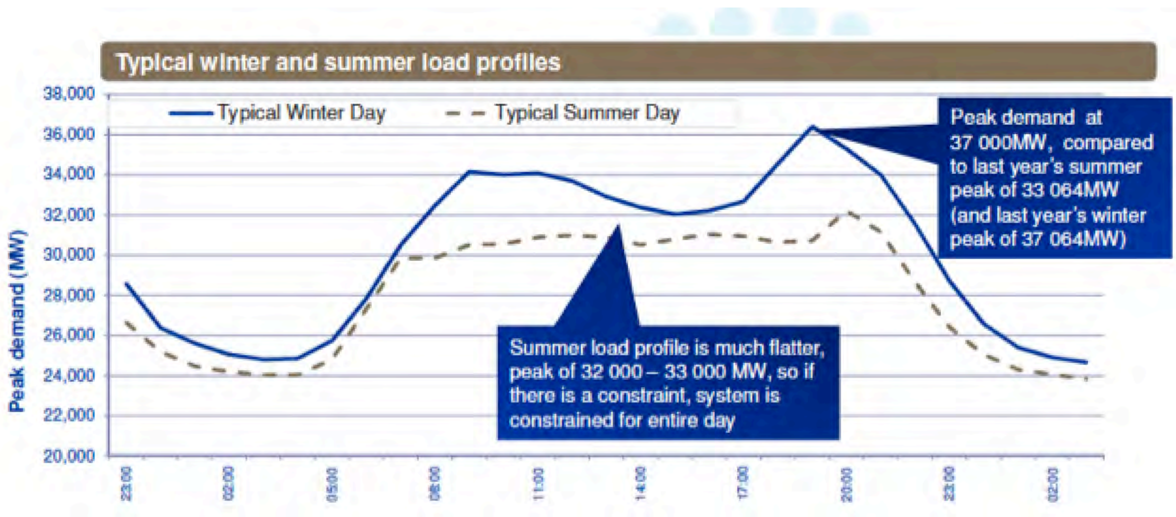

Figure 22: Average Daily load curve (Knox 2013)

Further figure 22 represents an aggregated load profile for SA peak periods differ depending on the season (summer or winter)

Winter: There are 2 clear peak periods

Period 1: Between 7:00 and 10:00
Period 2 Between 18:00 and 20:00
Summer there is flatter curve however there are 2 peak periods
Peak period 1: Between 7:00 and 19:00
Peak period 2: Between 19:00 and 21:00

Typically the flatter curve would indicate the system has greater vulnerability to downtime or externalities.
These graph curves are important when deciding the most appropriate RES for the system, which already is constrained and subject to failures as a result of a lack in system robustness and variety. This must be accounted for when attempting to create a system, which is sustainable as a result of an aggregation of, distributed sources.

Observations

While this data is not surprising, its relation to revenue generated highlights that is in a constrained power grid with peak demand shortfalls, the high peak demands of the largest user sector does not lend itself towards a sustainable system from the viewpoint of revenue generation for eThekwini or system robustness. However, the secure and quality supply of energy to the bulk sector is critical for the economic landscape and as such, curbing supply is not feasible. Reducing demand and shifting off-peak power capacity to peak demand periods is crucial in maximising the current grid capacity, creating a system which is more effective, efficient and sustainable in the long term.

5.4 Renewable and offsetting potential

As highlighted in the previous section, adopting a RES is crucial in helping alleviate system stress though larger variety in supply and greater horizontal system structure, however this supply needs to be designed for so as not to reduce the systems ability to respond to sudden changes with the potential ability at causing a system wide failure. Its for this reason that traditional energy production methods have been favoured, namely for their ability to respond to sudden ramping up in demand by having a base load with flexibility. Sudden changes in demand and supply, however, create system stresses such as voltage imbalance and harmonic distortions, which if left unchecked have the ability to cause greater system issues, then even a pure lack of supply. This issue is exasperated when supply margins are flatter and closer to actual demand, leaving the system open to collapse due to sudden increases in demand, on the other side when the system demand is low and supply is high, the efficiency of the system is reduced. A renewable resource such as Solar PV has the characteristic of being intermittent with sudden and drastic changes in production; this chart eristic when aggregated at a system level creates a system, which is environmentally friendly while inherently unstable and non-effective. Counteracting this is reliant on a storage method with the ability to flatten out delivered power as well as absorb system imbalances. The following section will quantify the Solar potential for the case study site as well as identify a means of effectively delivering this renewable resource to the grid.

Table 4: TOU periods

TIME PERIODS	MONDAY – FRIDAY	SATURDAY	SUNDAY
22:00-06:00	OFF-PEAK	OFF-PEAK	OFF-PEAK
06:00-07:00	STANDARD	OFF-PEAK	OFF-PEAK
07:00-10:00	PEAK	STANDARD	OFF-PEAK
10:00-12:00	STANDARD	STANDARD	OFF-PEAK
12:00-18:00	STANDARD	OFF-PEAK	OFF-PEAK
18:00-20:00	PEAK	STANDARD	OFF-PEAK
20:00-22:00	STANDARD	OFF-PEAK	OFF-PEAK

Table 4 represents the current TOU periods, which are crucial when deciding the feasibility of RES, as is clear they correspond to the peak periods from the previous section.

5.4.1 Solar potential over 15year period

The client expressed a desire for his building to become more sustainable and cost effective in light of continual energy price increases, when surveyed the only renewable resource known was Solar PV which he expressed desire to adopt mainly due to the potential to decrease his demand and reduce his buildings footprint. For this reason Solar PV was chosen in the case study.

System requirements

- The system must not disrupt business operations during installation, operation or in case of system failure;
- The total budget was R1 500 000;
- Payback period was to be a maximum of 5 years;

- Demand reduction of 5%.

While environmental considerations were a driver for the installation, the economics of the project had to be feasible in order for adoption. The short payback period of 5 years was due to no previous hands on knowledge of solar systems and thus their life span and operating costs were not clearly understood and trusted from the supplier. This was so that the risk of investment was reduced. Table 10 below summarises the first iteration of the solar investigation.

Outcomes

From Table 10 it is clear that of the requirements, the only one able to be met is number one. Technically two would also have been met, however as the system failed on three and four, it would require more financial input to achieve those benchmarks and thus as a consequence two could also be deemed out of spec.

For a 60kWp system there is a payback period of 13.1 years and a decrease in demand of between 4.7% and 4.2% table 11

Table 5: Returns on solar PV current scenario

Payback Period	13.1 Years
IRR	1%
ROI (nominal)	7%

Assuming: Annual electricity price increase of 12.5% as has currently been approved by NERSA

Accelerated deprecation for renewable investment stands (50% year one, 30% year two, 20% year three)

Calculated at ITOU rates with predominate use occurring during standard rate periods

Discussion

At current market conditions, the project as it would be unfeasible and as such a potential annual carbon reduction of 81.6 tons was not realised a further annual 81.6 MWh of energy production was also not realised. Above the environmental benefits not realised the spending of R1 400 000 has economic effects not quantified in this investigation.

If it is assumed the client was unwilling to change the system requirements, what is needed to ensure this system would have been adopted? This is down to key areas of focus.

Area one: Energy produced should be tax deductible, energy use is an expense, and hence energy produced thus in effect becomes an income and is taxable. While this is not a direct tax, the indirect consequence of saving energy through renewable production is a decrease in the cost of energy and thus an increase in income.

Potential consequences: This alone would not be enough, however there is an improvement.

Table 6: Returns on Solar PV with Tax changes

Payback Period	11.4 Years
IRR	5%
ROI (nominal)	33%

Justification: While the renewable system is deemed an asset and subject to depreciation claims, the energy produced should be separated on paper from the system itself and be tax deductible due to its contribution to the grid supply.

Area two: All energy supplied to the grid during standard or peak periods from ITOU customers should be compensated at a rate proportional to the highest charged rates and not just ITOU rates or mega flex rates of bulk Eskom supply.

Table 7: Mega flex Eskom tariff for eThekwini

Mega flex tariff	High Season (Jun-Aug)	Low season	Average	Residential Tariff	Income/ Kwh
Peak Rate (R.c)	228.14	74.14	112,64	129,39	16,75
Standard rate (Rc)	69.10	51.22	55,69	129,39	73,7
Off-peak Rate (Rc)	37.54	32.50	33,76	129,29	95,53

Potential consequences: While a combination of tax incentives and increased purchase prices reduce the payback period to 7,3 years, both fail to reduce payback period to within a clients requirements. From Table 9 a payback period of 5 years is only achievable at a buy back price of R1, 78

Table 8: Results of solar return at average mega flex peak rate

Payback Period	7,3 Years
IRR	12%
ROI (nominal)	104%

Justification for higher feed in tariffs: Purely looking at mega flex and residential tariffs is not sufficient in justifying a feed in tariff of R1, 78, however if one takes into account the effects of load shedding is the rate of R1, 78 justifiable?

Table 9: Loss/savings per KWh for each season and tariff structure

Tariff	High	Low
ITOU	R0, 16	R0, 12

CTOU	R0, 36	R0, 65
RTOU	R0, 39	R1, 15
Residential	R1, 21	R0, 67

Red indicates savings for eThekwini

From Table 9 it is clear that during times of shortfalls eThekwini's response with regards to load shedding should differ between both seasons.

High Season: It is economically viable for restrictions to be placed on RTOU and residential tariff users, while keeping a supply to CTOU users would restrict losses

Low season: It would be more economical to restrict supply to the ITOU consumers while keeping supply constant for the RTOU sector, it should be noted that the RTOU tariff is not active yet while pending approval from NERSA.

In effect taking an average across the year there is a theoretical average loss in profits of R0, 98/kWh due to loss of supply. If for the sake of grid supply security eThekwini were to justify a higher rate of R1, 78 needed for a feed in tariff then in effect for every Kwh of in feed at the increased tariff, and assuming this was on a level sufficient enough to avoid load shedding then the net affect is a profit of R0, 32 per kWh due to an avoidance in loss of supply across the grid equating to a net profit of roughly R 36 000 and the increased investment from the private sector in renewables

5.4.2 Summary of results

From the above investigation is evident that solar is not currently viable for the client if requiring a short 5 year payback, however if a tax incentive and increased feed in tariff is applied the payback period is reduced in line with what is feasible for the clients business with the added advantage of increased income for eThekwini, resulting in a more sustainable grid.

Solar PV Energy summary	Summer	Winter	Total	Assumptions
Power Produced (MW/year)	63.6	18,00	81,6	Day length Summer 12 Hours Day length winter 10. 5 hours
Building energy use (MWh/year)	1152,00	448,00	1600	
Percentage change	72,00%	28%	100%	
Usage reduction	5.52%	4,01%	5,1%	
Peak demand reduction (kW)	19,4	18,6		
Percentage change	4.7%	4,2%		
Co2 mitigated (t)	63,6	18	81,6	

Figure 23: Demand reduction potential 60KWp system

Further to this figure 23 highlights that the clients building has the potential to offset 81,6 tons of Co2 per year and reduce annual demand by 81,6 MWh. Representing a 5.1% building use reduction.

Table 9: Solar PV 15 year performance summary at current market conditions

Solar PV																
Size (KWp)	60															
Power produced (KW)	81600															
CO2 offset (tons)	816	10 years														
Demand saving																
Life span (years)	20															
Cost (Rands)	1400000															
Vat @ 14%	172000															
Depreciation claim	196000	Year one														
	117600	Year two														
	78400	Year three														
Cell degredation	0,95	15 years														
Electricty cost increase	1,125	per year														
Standard time rate	0,6394	average														
Savings from solar		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		52175,0	55762,1	59595,7	63692,9	68071,8	72751,7	77753,4	83099,0	88812,0	94917,9	101443,5	108417,7	115871,4	123837,578	132351,412
Tax cost due to savings	28%	-14609,0	-15613,4	-16686,8	-17834,0	-19060,1	-20370,5	-21771,0	-23267,7	-24867,4	-26577,0	-28404,2	-30356,956	-32443,997	-34674,522	-37058,395
	Total	37566,0	40148,7	42908,9	45858,9	49011,7	52381,3	55982,5	59831,3	63944,7	68340,9	73039,3	78060,7	83427,4	89163,1	95293,0
Cash flow Projections		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		37566,0	40148,7	42908,9	45858,9	49011,7	52381,3	55982,5	59831,3	63944,7	68340,9	73039,3	78060,7	83427,4	89163,1	95293,0
		172000	117600	78400												
		196000														
Income	-1400000	405566,0	157748,7	121308,9	45858,9	49011,7	52381,3	55982,5	59831,3	63944,7	68340,9	73039,3	78060,7	83427,4	89163,1	95293,0
Cash Flow	-1400000	-994433,97	-836685,28	-715376,36	-669517,46	-620505,75	-568124,50	-512142,03	-452310,76	-388366,10	-320025,24	-246985,95	-168925,20	-85497,78	3665,28	98958,29
Year		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Payback Period	13.1 Years															
IRR	1%	See Apendix														
ROI (nominal)	7%	See Apendix														

5.5 Chemical storage potential

A fundamental characteristic of renewable energy resources is their intermittence, against traditional fossil fuel based production methods, renewable technology, while sustainable, is stochastic and generally supply cannot be made to coincide with demand requirements. As a result of this a sustainable grid requires more then just renewable adoption, it requires a means to embrace renewable, while maximising the current grid structure. Adopting a chemical storage technology enables renewables, or the traditional fossil based energy to be used when required. There is other numerous advantages such as frequency control, voltage support, harmonic compensation, UPS capabilities etc. It is however its ability to assist with load levelling a peak shaving that is of most importance in this investigation.

Table 11: Comparison of energy storage systems (Vazquez et al., 2010)

Type	Energy Efficiency (%)	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Life (cycles)	Self Discharge
Pb-Acid	70–80	20–35	25	200–2000	Low
Ni-Cd	60–90	40–60	140–180	500–2000	Low
Ni-MH	50–80	60–80	220	< 3000	High
Li-Ion	70–85	100–200	360	500–2000	Med
Li-polymer	70	200	250–1000	> 1200	Med
NaS	70	120	120	2000	–
VRB	80	25	80–150	> 16000	Negligible
EDLC	95	< 50	4000	> 50000	Very high
Pumped hydro	65–80	0.3	–	$>$ 20 years	Negligible
CAES	40–50	10–30	–	$>$ 20 years	–
Flywheel (steel)	95	5–30	1000	> 20000	Very high
Flywheel (composite)	95	> 50	5000	> 20000	Very high

There are numerous storage methods, Table 11 highlights the variations between efficiency and cycles of life, to this end, and Pb-Acid was chosen due to the vast literature and real life examples of installations. Along with its lower costs and relatively extended cycle life, it was deemed the most appropriate technology for integration into our existing grid structure.

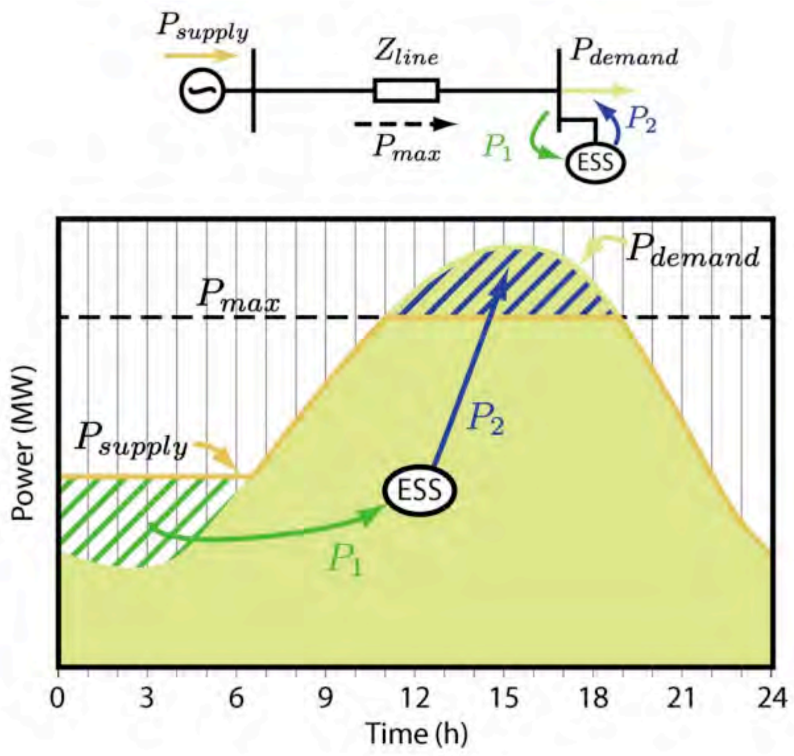

Figure 24: Peak demand shaving example (Vazquez et al., 2010)

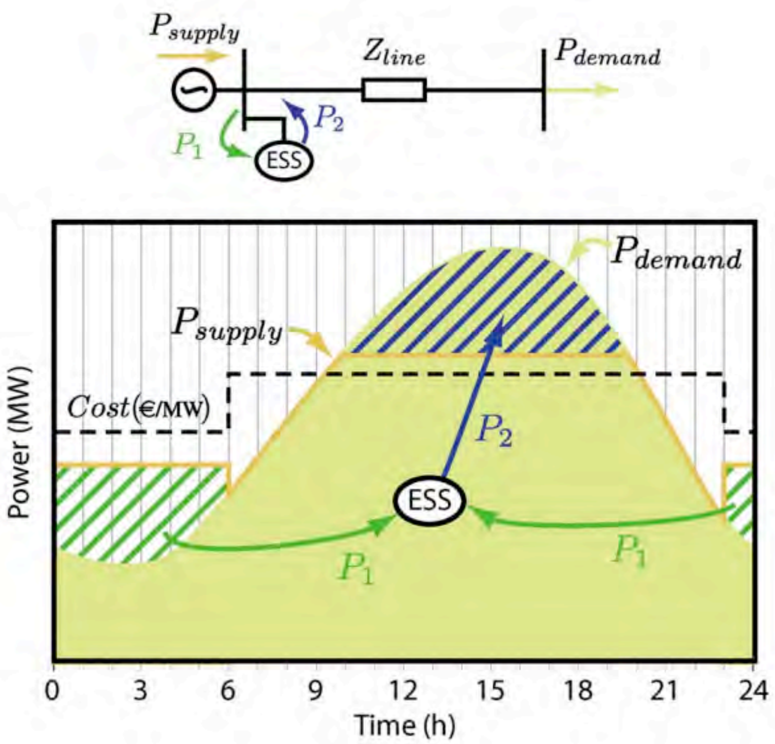

Figure 25: Energy Arbitrage example (Vazquez et al., 2010)

Figure 24 and 25 above illustrate the goal of adopting a battery energy storage system (BESS) refers not just to increased renewable supply it also encompasses how we use what we produce. BESS have the ability to create a more stable grid, greater system robustness and reduce the grids vulnerability to fluctuations in renewable supply.

As previously with regard to the client, their requirements stayed constant.

Requirements from system

- The system must not disrupt business operations when being installed, during operation or in case of system failure;
- The total budget was R1 500 000;
- Payback period was a maximum of 5 years;
- Demand reduction of 5%.

The client expressed his desire to become *more sustainable*, however only if the economics made sense. Solar PV proved non viable however the client was asked weather a saving in another area would offset the cost of solar PV to which he agreed. Again the short payback period of 5 years was due to no previous hands on knowledge of BESS and thus their life span and operating costs were not clearly understood and trusted from the supplier. Table 12 below summarises the first iteration of the BESS investigation at current market conditions.

Outcome

At 120 KW the BESS system is relatively small in energy storage terms as well as land size requirements as the system is contained in a 20 foot standard shipping container of (L: 6m H: 2.4m W: 2.4m) Total: 14.4^{m2}. See fig 26. Able to meet all the clients requirements as per table 13 the BESS system by itself from a purely economic framework would be justifiable, however the client was willing to adopt Solar PV if the combination of Solar and BESS was feasible against his initial requirements.

Figure 26: Example of Similar sized BESS unit

Table 12: Chemical Storage @ ITOU rates

Battery Storage												
Size (kW)	120											
Nominal energy rating (kWh)	500											
Demand reduction(kW)	84											
Life span (years)	10											
Cost (Rands)	1500000											
Vat @ 14%	210000											
Depreciation claim	210000	Year one										
	126000	Year two										
	84000	Year three										
Cycle depth	80%											
Efficiency	84%											
Cycle/day	1											
Discharge time	5											
Electricty cost increase	12,5%	per year										
Season	Low Season	High Season	Low Season	High Season	Low Season	High Season	Low Season	High Season	Low Season	High Season		
	ITOU		CTOU		RTOU		Embedded Residential		Residential			
Peak rate	0,8318	2,4123	1,2708	2,5758	1,8963	1,8963						
Off peak rate	0,4008	0,4526	0,5947	0,6278	0,7017	0,7017	0,62. Kwh Supplied		1,2939			
Income from system	ITOU rates	1	2	3	4	5	6	7	8	9	10	
Arbitrage		133873	150607	169433	190612	214438	241243	271398	305323	343488	386424	
Demand savings (R)	76,40	77011	86638	97467	109651	123357	138777	156124	175639	197594	222293	
Notified demand savings (R)	24,13	24323	27363	30784	34632	38961	43831	49310	55473	62408	70209	
	28%	-65858	-74090	-83351	-93770	-105492	-118678	-133513	-150202	-168977	-190099	
Net Income	-1500000	169349	190518	214332	241124	271264	305172	343319	386234	434513	488827	Total
Cash flow	-1500000	589349	316518	298332	241124	271264	305172	343319	386234	434513	488827	3674652
Cash flow analysis	-1500000	-910651,05	-594133,48	-295801,22	-54677,42	216586,85	521759,16	865078,01	1251311,71	1685824,62	2174651,65	
ROI	145%											
Payback Period (years)	4.1											
IRR	21%											

Table 13: Combined BESS and Solar PV system

Solar PV			Battery Storage										
Size (KWp)	60		Size (kW)	120									
Power produced (KW)	81600		Nominal energy rating (kWh)	500									
CO2 offset (tons)	816	10 years	Demand reduction(kW)	84									
Demand saving			Life span (years)	10									
Life span (years)	20		Cost (Rands)	1500000									
Cost (Rands)	1400000		Vat @ 14%	210000									
Vat @ 14%	172000		Depreciation claim	210000	Year one								
Depreciation claim	196000	Year one		126000	Year two								
	117600	Year two		84000	Year three								
	78400	Year three	Cycle depth	80%									
Cell degredation	0,95	15 years	Efficiency	84%									
Electricty cost increase	1,125	per year	Cycle/day	1									
Standard time rate	0,6394	average	Discharge time	5									
			Electricty cost increase	12,5%	per year								
Savings from solar		1	2	3	4	5	6	7	8	9	10		
Energy Saved		52175	55762	59596	63693	68072	72752	77753	83099	88812	94918		
Tax cost due to savings	0%	0	0	0	0	0	0	0	0	0	0		
	Total	52175	55762	59596	63693	68072	72752	77753	83099	88812	94918		
BESS	ITOU rates	1	2	3	4	5	6	7	8	9	10		
Arbritage		133873	150607	169433	190612	214438	241243	271398	305323	343488	386424		
Demand savings (R)	R76,40	77011	86638	97467	109651	123357	138777	156124	175639	197594	222293		
Notified demand savings (R)	R24,13	24323	27363	30784	34632	38961	43831	49310	55473	62408	70209		
Tax	28%	-65858	-74090	-83351	-93770	-105492	-118678	-133513	-150202	-168977	-190099		
	Total	169349	190518	214332	241124	271264	305172	343319	386234	434513	488827		
Cash flow Projections		1	2	3	4	5	6	7	8	9	10		
Combined income		221524	246280	273928	304817	339336	377924	421072	469333	523325	583745		
Vat Claim		382000	0	0	0	0	0	0	0	0	0		
Depreciation		406000	243600	162400	0	0	0	0	0	0	0		
Total	-2900000	1009524	489880	436328	304817	339336	377924	421072	469333	523325	583745		
Cash Flow	-2900000	-1890476	-1400596	-964268	-659452	-320116	57808	478881	948213	1471538	2055283		
Year	-		2	3	4	5	6	7	8	9	10		
Payback Period	5.9 Years												
IRR	12%	See Apendix											
ROI (nominal)	83%	See Apendix											

5.5.1 Summary of Investigation

If both Solar PV and BESS were combined at current market conditions the payback period would still fall outside of the clients requirements. The barriers to renewable and BESS adoption as a combination are still the low feed in tariffs, however the combined system on paper presents a more feasible option. However, by itself as a purely arbitrage system, BESS is viable in economic terms for an investor.

Table 14: Combined return

Payback Period	5.9 Years
IRR	12%
ROI (nominal)	83%

There are three distinct advantages to an integrated solar and storage system

- Management and mitigation of peak demands;
- Ability to deliver grid support services to improve grid supply quality and availability;
- Emergency backup during critical load periods.

In terms of sustainable this method of BESS does not fulfil the primary objectives of brining usage within the bounds of the earth's carrying capacity and as such if the client were to solely adopt a BESS system it should be viewed as a failure in terms of sustainability. If one were to judge the system on pure efficiency, then in terms of grid efficiency the adoption of BESS Would be highly successful. Developing a method for combining renewable and storage technology so as to create an effective distributed RES will rely on methods discussed through the literature review, namely the creation of a horizontal Multi-agent system based around independently operating agents within the grid. A discussed previously there are emergent properties, which are bale to ensure sustainability's success, however quantifying those values is almost impossible. Instead if a consumer establishes there own identity through Microgrid adoption there are simple economic considerations, which can benefit their adoption of RES.

5.6 Developing Microgrids

Why is there a need for developing microgrids? The answer I found lay in three specific areas, while there are other areas that could be discussed, the following are perhaps the most applicable to the average building user. (1) Area one: Economic (2) Area Two: Behavioural.

The architecture of a system as Whitney (2006) highlighted, has the ability to either determine or influence the behaviour and property of system. Adopting microgrids alters the structure and thus the dynamics of the Microgrid system itself and by extension the broader interconnected systems.

5.6.1Economic justification

The current supply model has the municipality as the sole supplier and biller of energy to the end user. This exposes the end-user to various charges involved in the supply and use of that energy. The primary charge (above the energy cost) being a 22.5% voltage surcharge to step the voltage supply down from 11kVA to a usable 400v. That surcharge is calculated on the total bill (including all network demand charges) this charge is as a result of equipment cost and maintenance. With around 35% of the total energy costs being related to supply charges above actual electricity costs, this is an area that is often overlooked in energy efficiency measures as it does not provide any direct environmental benefit and investment does not provide any production capacity.

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Figure 27: Current Grid Set up

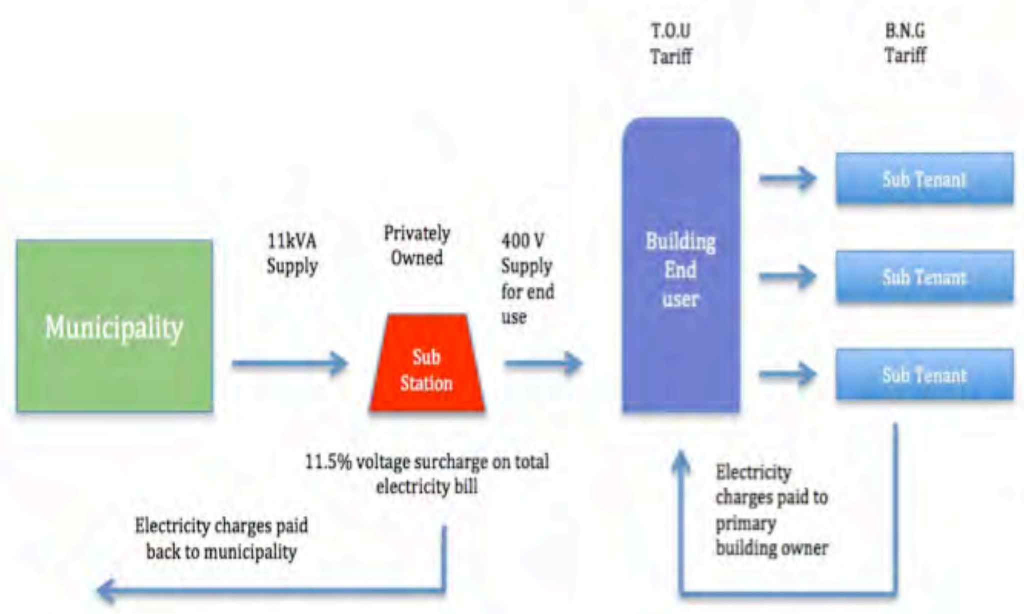
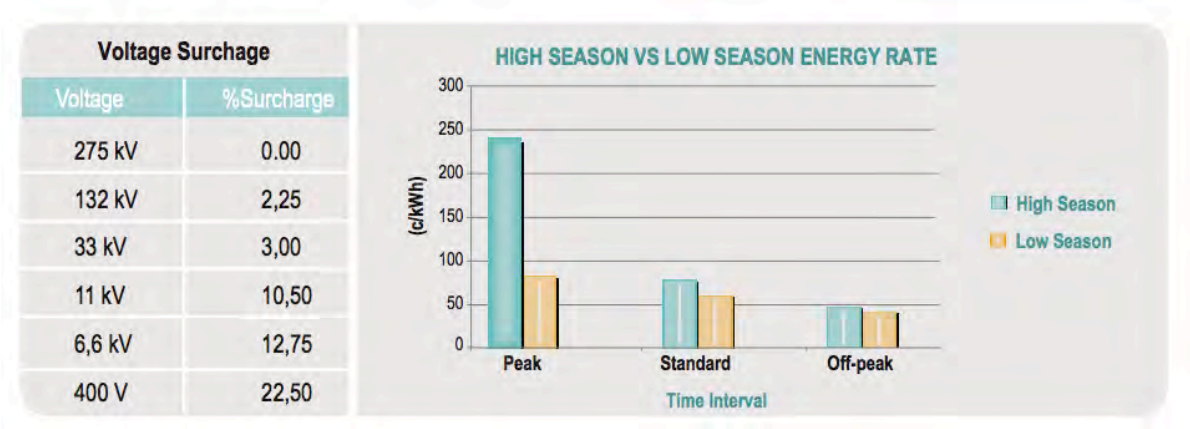


Figure 28: Proposed Grid set up

The new proposed model (as outlined in Fig.28) has the municipality as the bulk supplier, and the end-user as the secondary supplier and provider of energy to the separate sub meters in the building that supply the tenants. This has numerous advantages. First of all, an immediate reduction in monthly electricity bills of 12%, in itself would be sufficient to justify an investment. Secondly, the building owner can actually become a supplier of electricity; this allows the owner to take advantage of the two different pricing structures. Supply is at T.O.U tariff, while sub supply is at B.N.G. This allows the building owner to in essence charge a premium of on average 25c per kWh for the sub meters. Thirdly, the adopted solar plan has the effect of allowing the building owner to take advantage of the lower T.O.U tariff, while receiving payback from the solar electricity at the higher B.N.G rate. This provides greater flexibility and predictability for income form a solar retrofit and battery storage adoption, reducing overall risk and increasing the probability of sustainability.



Voltage Surchage

Voltage	%Surcharge
275 kV	0.00
132 kV	2,25
33 kV	3,00
11 kV	10,50
6,6 kV	12,75
400 V	22,50

Figure 29: Voltage surcharge (EThekwini, 2015)

With Local grid supply via a distribution ring at 11KV. Accessing the 11KV distribution ring is reliant on the establishment of a Microgrid through the installation of a mini transformer with 11KV feed. This would in effect mean the building has the potential to exist as an island from the main grid in case of a system failure or if the client wished to develop a fully self supporting system. Currently the economic benefits of microgrids adaption are deemed the most crucial as a means of providing greater feasibility for a RES system to be developed on site.

There are two components to this, if we use off-peak to charge the BESS system the energy cost is in effect 12% lower, while when we sell it (by using it at Peak periods) the energy savings are 12% higher. This is summed up below for the system as a functioning whole.

Payback Period	3,7 Years
IRR	29%
ROI (nominal)	144%

Figure 30: Combined return with Microgrid adoption

A payback period of 3,7 years is well within the clients requirements, and far below either Stand alone Solar PV Or BESS systems. This highlights how price sensitive a RES is.

5.6.2 Behavioural Justification

Security is crucial component of investing, by establishing the building, as a Microgrid the energy environment is partially segregated from the broader energy environment. A Microgrid system creates a system, which is definable and has a greater degree of control then a system integrated into the broader grid system. This increased security and definable boundaries means that in the climate of current shortfalls and sustainability calls, the segregated system of a microgrids has the ability to produce, off set and account for their individual’s energy system. It’s this accountability, which provides the self-motivation for investing in a sustainable solution to an individual’s energy system that is not solely reliant on traditional means of supply.

5.6.3 Summarising the investigation findings

The results for the investigation were mixed and varied; at the beginning of the investigation the objective was to create a user that was more effective and in effect sustainable. If these are rigid objectives then a either Production, storage or system structure alone are not enough to satisfy the definition of sustainability, It was found that achieving sustainability relied on a combined approach with the aggregation of the outcomes tending towards a system which is both sustainable and cost effective so as not to drive away investment potential. Table 15 below summaries the secondary financial component of sustainability.

Table 15: Combined financial results of investigation

Savings from solar		1	2	3	4	5	6	7	8	9	10
Energy Saved		52175	55762	59596	63693	68072	72752	77753	83099	88812	94918
Tax cost due to savings	28%	-14609	-15613	-16687	-17834	-19060	-20370	-21771	-23268	-24867	-26577
	Total	37566	40149	42909	45859	49012	52381	55982	59831	63945	68341
BESS	ITOU rates	1	2	3	4	5	6	7	8	9	10
Arbitrage		133873	150607	169433	190612	214438	241243	271398	305323	343488	386424
Demand savings (R)	R76,40	77011	86638	97467	109651	123357	138777	156124	175639	197594	222293
Notified demand savings (R)	R24,13	24323	27363	30784	34632	38961	43831	49310	55473	62408	70209
Tax	28%	-65858	-74090	-83351	-93770	-105492	-118678	-133513	-150202	-168977	-190099
Total		169349	190518	214332	241124	271264	305172	343319	386234	434513	488827
Voltage savings		228000	256500	288562,5	324632,813	365211,914	410863,403	462221,329	519998,995	584998,869	658123,728
Cash flow Projections		1	2	3	4	5	6	7	8	9	10
Combined income		434915	487166	545804	611616	685488	768417	861523	966064	1083456	1215292
Vat Claim		424000	0	0	0	0	0	0	0	0	0
Depreciation		448000	268800	179200	0	0	0	0	0	0	0
Total	-2900000	1306915	755966	725004	611616	685488	768417	861523	966064	1083456	1215292
Cash Flow	-3200000	-1893085	-1137119	-412115	199500	884988	1653405	2514928	3480992	4564448	5779740
Year			2	3	4	5	6	7	8	9	10
Payback Period	3,7 Years										
IRR	28%	See Apendix									
ROI (nominal)	144%	See Apendix									

5.7 Investigation part two: Horizontal Energy infrastructure

5.7.1 introduction

If we succeed in creating sustainably effective individual consumers through Microgrid adoption, we would have only partially realised the true potential of intelligent individuals and their newly created systems. If these intelligent agents are structured within an intelligent network so that there is autonomous interaction with upper levels (vertical and horizontal) of the hierarchal energy system as well as the with the connected consumers then this intelligent network has the characteristic ability for being amongst others: self supporting, adaptive, active, cost effective, eco friendly and above all secure and stable. This final part of this investigation deals with theoretically creating a vertical structure within the energy grid, where the consumer plays a central role. The justification for a more vertical grid structure is as a result of the substantial aggregation of building consumption, and in theory the potential energy production potential inherent within the vertical structure in the form of an aggregation of buildings. This vertical structure is the corner stone of an intelligent/smart grid, however this system is one system within the confines of a "system of systems" from the weather system which impacts the energy system, to the social behaviour of the individual interacting with the energy system creating emergent challenges which need to be accounted for when designing or restructuring the energy system for the future. This redesign in the form of vertical structure creates an increase level of complexity, however a discussed in previous chapters its this complexity that when embraced has the potential to enable sustainability to emerge.

5.7.2 Producing a distributed Power plant

Is it possible to create a distributed renewable energy plant, comparable to a traditional centralized fossil fuel based plant? And if so, what exactly would it take to reproduce the production potential of a coal fired powered plant using distributed RES? And is it feasible that a virtual (virtual by nature of its separated components) renewable power plant could be a replacement for a traditional centralized power plant?

As the fourth largest coal fired power plant in the world when completed, Kusile is an ideal benchmark for comparison. Ideal due to its nature and reliance on fossil fuel for energy production, its nature as a centralized production method which is reliable in its output, yet inflexible in the nature of supply. With currents plans to build a similar size coal fired plant called "coal 3" there is a benchmark to which a RES could be justifiably compared and promoted as a viable alternative to what arguably is an out-dated technology which contributes large volumes of harmful Greenhouse gases to our environment.

At 16% of total Eskom supply capacity, Kusile is a large component of our power system, with a correspondingly large negative environmental impact. Large transmission distance also equate to transmission losses of around 10% for distance > 600km from the plant itself.

The main benefits of renewable production:

1. No continual input cost to produce energy after initial capital cost and some minor maintenance costs;
2. Production occurs closer to demand resulting in less transmission losses;
3. A RES system allows for supply to match demand resulting in less off-peak wastage;
4. A RES system evenly distributes peak load reducing infrastructure requirements;

Sustainability is achievable as renewable resources are non

5. Diminishing and produce zero carbon during production.

Table 16: Kusile coal power plant statistic

Size	4800 MW
Cost	118 000 million

Actual cost if operating costs included	282 000 million
Life span	60 years
CO_2 produced per annum	37 Million ton
Coal used per annum	17 Million tons
Downtime	10%
Average annual production	37900GWh
% Of Eskom annual production	16%
Fuel, operation and maintenance costs	25%
WACC of 8% over 30 years	
Average cost/Kwh produced	R1, 45

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Main benefits of renewables

- No continual input cost to produce energy after initial capital cost and some minor maintenance costs
- Production occurs closer to demand resulting in less transmission losses
- A RES system allows for supply to match demand resulting in less off-peak wastages
- A RES system evenly distributes peak load reducing infrastructure requirements.
- Sustainability is achievable as renewable resources are non diminishing and produce zero carbon during production,

Table 17: RES cost for Kusile sized supply

Required output	37000	GWH
Solar case study system	0,0816	1 Building
Systems to match Kusile	453432	
Cost per system	2100000	
Total cost	950	Billion

With a life span of 60 years, Kusile will be around for an extended period of time, requiring unsustainable practices to fuel the process due to its reliance on fossil fuel inputs. When compared to this a RES at R950 Billion, may sound beyond the reach of comparison, particularly when the system is only guaranteed to last a period of time far shorter then a large coal fired plant. However, if one considers the fundamental differentiate between the two in the form of the externalities placed on society through the technology, weighting the costs, while not entirely quantifiable, are justifiable.

Table 18: Estimated annual externality cost Kusile (Greenpeace 2010)

	Net output	Externality cost			
	GWh	Low (R million)	R/kWh (Low)	High (R million)	R/kWh (High)
Health	32 301	182.8	0.006	213.3	0.007
Climate change	32 301	3 148	0.097	5 334	0.165
Water	32 301	21 305	0.660	42 357	1.311
Mining	32 301	6 538	0.202	12 690	0.393
Total		**31 174**	**0.97**	**60 594**	**1.88**
Total excluding water for generation purposes*		**9 869**	**0.31**	**18 237**	**0.56**

A case study by green peace generated the following cost of externalities, assuming the same 25 year period as solar feasibly will last, the results shift slightly closer.

Assuming the lower calculated externality cost over 20 year the societal cost would equate to 700

Billion Rand, if transmission losses are ignored but the operating, running and input costs are included, over 20 years, Now the actual cost of Kusile is in the region of R863 Billion, far closer to the R950 Billion required to construct and run Kusile. Another consideration is the direct foreign financing received for Kusile from foreign banks and investors. Over 30 Years on a loan of that size the interest payment would equate to around R166 Billion rand at 8%. This in effect brings the total cost of Kusile over 20 years would be in the region of R974 Billion Rand, slightly above the R950 Billion a RES would cost.

Beyond just the numbers involved, its how the system is constructed that holds the greatest potential. Responsibility for construction is deferred from as single controlling entity to that of 450 000+, meaning risk is spread amongst a far greater percentage of the energy users. Investment values are correspondingly lower resulting in increased adoption rates and greater value for money. Sustainability being an inherently social issue is now thus solvable directly through a social mechanism and instead is not reliant on a centralised system driven intervention with only indirect links to the social cause of the issue.

5.7.3 more reasons for a Vertical grid structure

R950 Billion rand to meet only 16% of our annual energy requirement on paper seems like a vast investment, however if externalities and financing costs are included the number becomes on par with the traditional technology. The key part of this section was showing the reasoning for a more vertical grid structure, where the consumer is relied upon to provide grid supply. A Kusile sized power plat would require around 453 432 similar sized installations as the case study to the value of R2 100 000 each. The numbers suddenly become smaller when distributed amongst a large collection of consumers with the aggregated results of the systems equating to a single centralised coal fired plant

5.7.4 Altering the grid structure

If we embrace the principle of emergence, that whole entities exhibit properties, which are only attributable to the whole and not the aggregation of its parts. Then hierarchy is merely the principle that a whole entity is made up of smaller entities, which in them can be considered wholes. Thus in a hierarchal system, emergent properties denote levels within the hierarchal structure. This idea is linked to the notion of a systems engineer who seeks to maintain and reach the required emergent properties so that the system is able to meet consumer’s needs. With that in mind, can the current vertical hierarchal structured if centralised supply effectively cope with the complexities associated with the every changing social system? I argue that centralised supply is not able to effectively manage the complex nature of energy use. Mainly due to the aggregation of effect of large numbers of individual agents in a system lacking in hierarchal levels

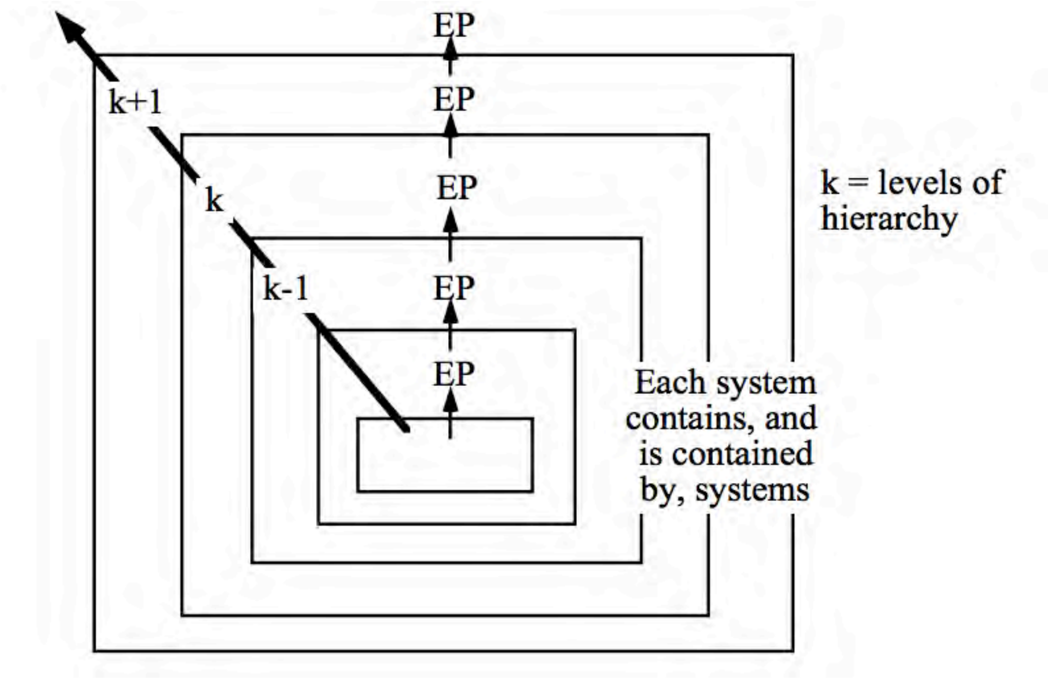

Figure 31: Emergence and Hierarchy (Hitchins, 2003)

If the notion that the current energy systems lacks sufficient hierarchal levels, are we able to manage the increased induced complexity by breaking supply up into manageable parts? I.e. microgrids.

Chapter six: Discussion

Microgrid development was proven to be justifiable on economic grounds, reducing payback periods while providing an income potential previously not evident. This increased economic potential enables sustainability measures to be a less risky proposition for business thus enhancing the probability of success through the associated reduction in risk. A 3.7-year payback period with a reduction of 36.8% in energy bills will significantly alter the business ability to compete in light of rising energy costs in the short term this reduction of risk and decrease in payback periods can provide justification for future adoption of increased renewable production. This adoption will enable a new enhanced level of knowledge to develop within the grid and its users. This will have a corresponding increased adoption rate of RES, resulting in the single agent system with its vertical hierarchal structure being replaced with a multi agent system, which has a more horizontal and distributed structure with greater variety in supply as well as enhanced system robustness. This reduces sustainability's success to a sum of its parts versus being reliant on the whole allowing the principle of emergence to drive sustainability in a more open and dynamic system. By providing the individual with an identity, enhanced sustainability thinking was promoted, in that actions now have direct and measurable consequences for one self as these actions not incrementally diminished or altered by the collective inaction.

Of fundamental importance is identifying if the stated objectives were met and if the results of the investigation are in line with the expected results when compared to existing case studies in a local and global context. All stated objectives in chapter one were met throughout this research paper. With a strong focus on the economic aspect as well as mindful observation of the sustainability component of the energy environment the research reached the stated objectives without sacrificing the primacy of one of another. When compared to a global case study as was discussed in chapter three, the theoretical identified potential of the system exceeds the achieved results of the existing system focused on. The Santa Rita jail (SRJ) Microgrid achieved a 98% peak demand offsetting vastly dwarfs the theoretical achievable 5% peak demand offsetting of the case study building. This is directly down to the limited scope of technologies employed as well as the cost limitations placed on the adoption of technology due to a low required payback period. The SRJ relied on a diverse mix of DER, in order to provide full autonomous operation. This study could not incorporate a vast diversification of energy sources as well having a differing objective of simply reducing energy use and not attempting to provide full autonomous capabilities.

While the case study lacked when in demand reduction when compared to the SRJ case study, one area where it exceeded expectations as well as surpassed the achievements of the SRJ case study is when it came to overall reductions in energy demand. The SRJ achieved a demand reduction of 15%, far below the identified 36.8% potential reduction in the investigation. This is primarily down to the large savings in tariff structures through migration to a Microgrid, coupled with the buildings load profile of sharp peaks during high TOU tariff periods which were able to be offset. A major limitation

There were several identifiable barriers to Microgrid adoption, three important areas of consideration are…

1. Are independent power producers allowed in local policies and codes?

2. Does policy allow DER to interconnect to the macro grid in parallel mode and islanding mode?

3. Is there and incentive and a demand for grid feed in

Arguably the answer to all three of those is, no. Policies have been tabled where IPP are allowed however this is more applicable to large scale IPP and not the micro scale customer IPP's which have been investigated in this paper. Interconnection is a tricky area, primarily due to the lack of adequate systems capable of regulating the feed in quality, grid supply when the microgrids is in island mode while not entirely applicable to this research is not however currently allowed. This is due to the system still being identified as a component of the macro grid and not as an entirely separate entity. This creates difficulties with regard to safety as there is no means of ascertaining weather the localised grid is DE energised o is being fed by a Microgrid in island mode. But beyond those two, there is a fundamental miss match in the economics when it comes to feed in tariffs, current feed in tariffs are well below redundant supplied TOU tariffs. This in itself prohibits the micro scale production of renewable energy, as there is a lack of financial incentive for adoption. A key observation in the report was the need for storage system capable of matching and exceeding the potential production of the solar PV system. This eliminates the scenario of over supply not being required in the grid as a result of low demand, resulting in wastage of the produced energy.

The ICC case study neatly illustrated the importance of having a storage system capable of matching the produced power. However the abstract reliance on EV's and their stored energy is viewed as a flawed concept. This notion is justified through the use of rationality theories discussed in the literature reviews as well as behavioural characteristics of individual agents in the system. The complex nature of a dynamically shifting storage system is not conducive to the creation of a stable and effective energy system as it introduces variations into a system which would be hard pressed to cope with a changing energy landscape. Focus should rather be given to existing battery storage technology.

Microgrid potential is clearly evident for an individual or business. However this benefit can be extended to the collective if accurate and real-time data is used to coordinate energy usage and renewable production. Allowing seamless energy export to the grid at a higher net rate then is currently afforded will further enhance the viability for renewable production promoting higher levels of investment in renewable generation and storage. This production can be used to supplement current supply deficiencies or in the long run can be used to replace the need for further non-renewable production means. This decentralised approach allows energy produced to be consumed in the same spatial frame, enhancing efficiency further as well as providing further incentive and control for municipalities to safe guard themselves against future shortfalls in supply. Above pure efficiency, a decentralised distributed system consisting of multiple sources creates a system which is highly effective and by extension sustainable. This has the potential to avoid Hardins tragedy of the common as well as providing a possible solution to the social problem created though an interconnected grid system and the failures of sustainability initiatives currently.

Chapter seven: Conclusion

Future studies need to focus on creating Microgrid communities where interests are aligned in such a way that renewable production and storage are optimised, allowing the Microgrid to exist solely using off-peak grid power while being a net energy producer in peak periods. This approach will provide energy security and financial risk reduction for the individual as well as allowing sustainability goals being achieved via a combination of individuals benefiting the collective as a whole, thus accelerating sustainability success through the use of multiple agents' actions. As discussed in earlier chapters, recreating a traditional coal power plant through renewables is reliant on a financial input far greater then what is feasibly possible through a single source of intervention, however when that financial cost is spread amongst the collective, and is provided by private individuals, then the goal for renewable adoption is infinitely more attainable with the collective benefiting as a whole, through a more secure and diverse grid supply which has increasing levels of sustainability. Going forward there are four areas of focus, which a particular focus is needed from a municipal point of view in order to drive adoption. Policy needs an increased focus on not just the technical but also the cognitive disposition of individual consumers in the form of

- Increased use of a loss aversion framework:

Humans are intrinsically loss averse, thus users need to be more aware of their usage and when they use energy. This is reliant on real time data and a direct link to the consequences of energy use. Merely using a TOU tariff is ineffective when the consumer assumes there is no other option. To this end based on earlier discussions of behavioural characteristics a change from Post paid TOU to prepaid TOU would enhance the loss aversion affect for the consumer as there is a direct relationship to how they consume energy. This would be facilitated through the adoption of Microgrid with enhanced grid communication in the form of real time data.

- Opt out, not in:

Sustainability will fail, if consumers in the system benefit through ignoring calls, which negatively impact the individual while benefitting the collective, Game theoretic principle, proved that the rational choice in the situation is selfishness in favour of personal gain. In the current grid set up this was proved to be the correct decision even with the resulting consequences being a failure in the system. Altering this is reliant on creating a system or policy, which can only be opted out of, and not merely be a system where there is a request for opting in. In effect sustainability and renewable technology becomes the default option and not merely the preferred and often ignored option this theory is based on numerous studies where altering the default option greatly increased adoption rates for an option which was previously ignored.

- Discount rates for Renewable and distributed resources need to be reduced:

High costs for Solar PV will always be a barrier to wide spread rapid adoption; this requires a concerted focus on methods or mechanisms able to reduce this factor. As discussed earlier a small increase in buy back prices as well as tax incentives could address this. However more is needed to reduce pay back periods and thus the risk of investment further. A viable option would be incorporation of the cost into building repayments or utility repayments, helping spread the original upfront cost of the system over a period of time. This however is reliant on government invest which perhaps is not currently available

- Effective design:

The future energy system structure needs to be design from the perspective of the user. This includes not just the technology but the policies and mechanisms used to drive adoption of RES. Simplifying and streamlining the adoption process will make the new RES systems inherently more user friendly and decrease the consumers aversion based on pure confusion and non clarity. Through reducing the number of factors needed to take into consideration as well as allowing more functional information to be able for the consumer to process. This has the antithesis of an increase complexity in designing the system to make it operate effectively, however the modular nature of microgrids and Distributed resources means this complexity is easily managed and an advantage in a vulnerable energy system.

By providing consumers with a platform to contribute to their own energy security, the potential aggregated consequence is improved grid security for the collective as well a system which coverts effectiveness rather then one which relies on rational consumers to be more efficient at a direct cost to themselves. A system with multiple agents acting within a hierarchy that exhibits increased horizontal and not vertical structure through multiple distributed energy sources will lead to a grid which is inherently sustainable and robust, one which is able to meet not just our current needs, but our needs in the future.

Chapter eight: Future recommendations

Three key areas are earmarked for future studies, (1) Policy recommendations and comparable international policy changes and the results (2) Inclusion of a larger mix of DER technologies beyond just chemical storage and solar PV (3) concurrent study of two interconnected buildings with differing energy mixes as well as energy profiles.

The largest barrier currently is the confusing mix of policies related to energy production and distribution, a simplified policy approach, coupled with an increased incentive for renewable adoption is important if any broad scale adoption is hope to be reached. Further to this the The application of the principles discussed in the literature review to two or more interconnected micro users, in an attempt to balance load requirements as well as energy production, theoretically affords a greater degree of efficiency and effectiveness of the systems deployed vs. that of a single energy user. The use of continual power metering Is also recommended in order to draw an accurate picture of how the systems operate in real time. This data can than be used to illustrate to the building energy managers, in real time, the deficiencies in the system and allow them an opportunity to correct as such. This data can also act as a benchmark for future system adoption and expansion as well as provide a case study for further adoptions in differing fields.

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Appendix A: Published papers

THE USE OF BEHAVIOURAL MODELLING TO DEVELOP SMART BUILDING INFRASTRUCTURE IN SOUTH AFRICA

C. Loggia*, D. Hayman, V. Tramontin
*Corresponding Author: Telephone: +27(0)312601771;e-mail: Loggia@ukzn.ac.za
University of KwaZulu-Natal, School of Engineering, Howard College, 4041 Durban, South Africa.

ABSTRACT AND KEYWORDS

PURPOSE OF THIS PAPER: This paper aims at critically analysing the existing approach towards energy supply and sustainability, highlighting the role that Microgrid development can play in embracing and shaping user behaviour while leading to increasing investment in Renewable and Energy efficiency measures.

DESIGN/METHODOLOGY/APPROACH: The research relies on an interdisciplinary approach towards understanding the underlying complexities involved when developing a new energy model in the form of a theoretical approach, along with a case study in Durban.

FINDINGS: Microgrid adoption for the case building has a resultant minimum decrease of 11.5% of total energy spent with a potential 36.8% decrease, providing accelerated payback periods for renewable production and storage technologies with further potential for grid interaction.

RESEARCH LIMITATIONS/IMPLICATIONS: Quantifiable benefits/implications due to behavioural characteristics in a complex setting are subjective and were based on perceived utility of the user; heuristics can alter the user reported results

PRACTICAL IMPLICATIONS: The greatest design challenge is how to make socio-economic systems compatible with social imperatives and boundaries, whilst enabling co-evolution with the socio-technical system of energy supply, active agents within the energy grid have the ability to enhance this co-evolution.

WHAT IS ORIGINAL/VALUE OF PAPER: Microgrids have the ability to enhance socio-economic outcomes thus enabling sustainable energy practices with added broader socio-technical benefits.

KEYWORDS: Sustainability, smart grid, Microgrid, Interdependency, behavioural system

INTRODUCTION

Energy is an integral part of any developing economy; linked to poverty alleviation, job creation, economic growth, socio-economic progression and environmental health. As a social responsibility of the Government, Energy and its supply are explicitly linked to the enhancement in the standard of living for the population at all income levels. The challenges faced, and solutions, are both interdependent and integrated. Government often prefers integration to high degrees of interdependency, which is clearly demonstrated in the current crop of energy policies and action plans promulgated. In governmental terms, increased energy integration carries with it the connotation of the opening up and expansion of trade in energy supply on the side of the state, with the gains from supply enhancing economic welfare. Increased energy interdependence has the consequence of creating more independent trade partners (South African citizens or municipalities) increasing the risk of financial instability and reducing economic gains. This favouring of integration on the part of the state through the form of a linear single-agent system reduces the “transparency” of the energy market while increasing overall control [1]. However, levels of integration and interdependency need to be balanced and carefully coordinated in order to avoid the reduction of government’s ability to react to energy or financial crises through the implementation of national policies or action plans. The type of system within which these policies are shaped, plays a significant role in attaining sustainability. Nevertheless the current single-agent system is inherently highly complex in nature, due to the centralised agent lacking the ability to create coordination among solutions when dealing with fixed complex tasks [2]. The present research is part of an on-going project focused on enhancing energy efficient measures by developing a new multi-agent system with a basis in social behavioural models. This paper seeks to critically analyse the existing approach towards energy supply and sustainability, challenging the linear model in favour of embracing inherent complexity through advancement of a non-linear system achieved via Microgrid development, highlighting how embracing and shaping user behaviour can lead to increasing investment in Renewable and Energy efficiency measures and overall grid sustainability.

BACKGROUND AND LITERATURE REVIEW

A complex system is a system consisting of multiple agents, arranged in structures which can exist at multiple scales and whose process of change is not reducible and describable at only one level of explanation or scale [3]. In a socio-techno system of energy use, solving the complex system or understanding the underlying complexity is reliant on drawing in the knowledge base from multiple disciplines in order to understand the dynamic relationships present at the micro and macro level [4]. This distinction between the micro and macro levels requires an altered approach when attempting to research the complex relationships present. With micro level complexity revolving around behavioural rules and the macro level incorporating environmental constraints, in the form of institutional, spatial and structural parameters, advocating an ontological perspective approach to researching and understanding not just the complex system but the underlying causes of the complexity represents a paradigm shift from the norm. This ontological viewpoint is often in conflict with the epistemological viewpoint in that there is no clear agreement on how the micro and macro levels interact and thus how emergent properties develop or affect each level [5]. With energy use and the quest for sustainable development being an intrinsically social problem, this disagreement means that developing an understanding of the socio-technical system is heavily reliant on our views towards the research itself along with the affect our decision making process has on the socio economic environment. This intrinsic openness with regards to the potential for varying interpretations on the externality of the world itself and of the micro and macro components of the complex system neatly highlights the potential inherent within the framework of a complex setting if the correct knowledge is present when attempting to embrace such a system.

Cognitive agents

With an energy model needing to address climate related issues as well as focusing on energy security and affordability, shifting from rigid linear policies detailing what needs to be done to ensure sustainability, towards a non-linear dynamic method of advocating what is possible if sustainability is achieved is optimal. This shift in thought turns the idea that the collective is a cognising agent, into the collective consisting of cognising agents, representing what is fundamentally a shift from the macro towards a description of the micro level based on causative assumptions and complex characteristics such as emergence and self-organisation. Facilitating the development of an adaptive, evolving complex energy system is reliant on a multitude of conditions drawn from an understanding of multiple theories in particular views from the below four theories are foreseen as being the best possible means of attaining sustainability.

- Economic theories: Energy is viewed as being a commodity and users adapt habits based on pricing mechanism. I.e. very simply expressing that increasing price will lead to a decrease in demand;

- Psychological theories: where energy use is viewed as being affected by stimulus response mechanisms and through the engagement of agents in the system;

- Sociological theories: where energy use is ultimately viewed as a system and daily habits and actions are significant. In essence, it views energy use as being a side effect of our daily activities and not of the view that we directly consume energy;

- Educational theories: where agents are viewed as being individuals within a collective setting, and that energy use is a skill shaped and altered by our everyday experiences [6].

Each theory holds a different view on what energy use is, however this complexity allows for a multiplicity of possible outcomes, each with not necessarily a negative outcome however each lacking the possible best case scenario. The term "*outcome*" is used over "*solution*" as ultimately the idea of a solution is fundamentally flawed in that there will always be a better scenario, particularly when dealing with the issue of sustainability. A nice representation of this is in the view that humans within a complex system will with time develop complex thoughts to their views of sustainability of future generations to that of a positive change in their overall environment. One commonality among the four branches is the development of the idea of what an individual is and how they position that individual within a system. There are two distinctly different views with varying effects of outcomes. Firstly, there is View one, where an energy user is viewed as an individual. And in particular an individual who is rational in their choice and in the actions and manners towards other individuals. Their actions are seen as being a direct consequence of the information available, or the external and internal prompts exhibited on them [7]. This guides their decision-making process ultimately resulting in the end action and the outcome of that action. In terms of the important characteristic of rationality, the individual has an interest in the outcome with a preferred preference of the various alternatives and who will make a decision that fulfils those preferences. This has the direct consequence of opening up an individual to high levels of uncertainty due to the reliance on knowledge of initial conditions and multiple unknown strategies.

Economic and psychological theories in general follow this view of what an individual is and represents what is in effect a linear model where the collective is a cognitive agent with its stimulus basis in the macro level.

Then, there is View two, that focuses more on the idea of interaction and not process, moving away from the moment of decision, towards how a decision can be made to be inevitable due to the interactions at multiple levels on the individuals, setting conditions within which a decision is formed. This view moves away from the idea of focusing on the individual towards a focus on the actors within the individuals systems, which set conditions shaping those individuals actions. Educational and sociological theories represent this view towards that which is non-linear, dynamic model based on the importance of the micro levels drivers.

Microgrid adoption has the potential to combine these two distinctly different views, moving away from an individualist model of behaviour in favour of socially oriented behavioural model, viewing energy use and sustainability as an inherently social problem (micro) with the ability to be shaped and guided by the infrastructure (macro) setting however with the knowledge that this shaping of the micro level reciprocally alters the macro.

Sustainability in current thought

A key component of neoclassical economic thought is the Rational Choice Theory (RCT)[8].This method for the quantification and justification of benefits exhibits an inherent instrumental rationality relationship (working directly to a solution through the identification of problems) between state and individual. Energy use (and, as an offshoot, efficiency in the face of shortages or greater calls for sustainability) is a socially interactive decision making process. At the level of the individual, instrumental rationality fails as a consequence of the individuals holding only partial control of the outcomes [9], because of a lack of clear understanding and assumptions of behavioural patterns of other individuals within the energy grid. In the current climate of calls for energy efficiency to prevent grid collapse, the inability of the individual to accurately determine their expected maximum utility's levels, often prevent sustainability measures from taking root. This inherent problem in the current sustainability framework will require an alternative able to include the role of individuals. An alternative to enhance energy sustainability is the enablement of individual players in the grid (consumers of all levels) to anticipate other individual's actions though rational and common knowledge assumptions. Energy supply and its subsequent use, is an inherently complex process to model and attempt to predict. Complexity is created through the many facets in the energy supply model (source, legislation, actors etc.) as well as the vast numbers of interconnections involved within the current grid. This is exasperated as the current grid model lacks an adequate degree of high-level technology adoption in order to map and track energy demand in real time and at every level of use. This in turn leads to a high level of non-transparency due the supply and demand levels not being able to be fully described and comprehended. This high degree of non-transparency inhibits sustainability efforts when spontaneous changes, weather in the grid itself or amongst the individuals linked to the grid, lead to a dynamic complexity that cannot be correlated or accounted for within the framework of energy sustainability actions. Neoclassical economics is driven by the assumption that humans are intrinsically self-interested [10], as exhibited by rational choice theory, while we do not actively seek to harm others or in that we do not have an overriding level of conceitedness leading to care of ourselves above others. We do however, have a unique sense of what the preferred state of order is, hence this self-interest governs our actions and opinions as well as how we account for these actions and opinions.

RESEARCH CRITERIA AND METHODOLOGICAL APPROACH

This paper is aimed at critically analysing the existing model towards energy efficient supply and sustainability through a theoretical approach and the development of a case study. Formulating the framework for which a complex multi-agent model can be adopted, embracing the inherently dynamic environment in which energy supply and subsequent use exists within. The literature review dealt with providing an alternative through the development of a complex system embracing behavioural characteristics, cultivating coordination within the framework of a higher knowledge base allows for previously segregated agents to effectively contribute to their own sustainability as well as the collectives. The scope of the case study is still developing, with the first stage investigating the pure economic benefit for the building owner in establishing a Microgrid. This does not aim to exclude the other benefits associated with Microgrids; however, it provides the basis for commercial adoption. The case study involved potentially establishing the Microgrid through consultation with eThekwini electricity and relevant renewable companies Data was captured through, installing (temporarily) a meter to conduct an energy audit. The findings were then presented to the building owner with the aim of adoption. Discussions post-data gathering gave insights into the decision process an individual goes through prior to coming to a conclusion on a subject such as sustainability of energy supply.

CASE STUDY: A MICRO-GRID DEVELOPMENT IN ETHEKWINI (DURBAN, SOUTH AFRICA)

The case study incorporated a relatively small Microgrid (µgrid), which was developed and conceptualized with the primary focus on reduction of business-operating cost, through enabling the building owner to take control of his energy environment, thus making the business more cost competitive in the current market place. This solely focused on the benefits or a single building and did not focus on the cooperative potential between neighbouring buildings of differing but potentially mutually beneficial energy use. In this case study there are two agents: Agent one being the DO (eThekwini municipality) and Agent two being the factory owner/ µOP. Development was initially proposed in three stages:

1. Stage one: Solar Adoption
2. Stage two: Chemical storage
3. Stage three: Microgrid Adoption

Justification on financial grounds for agent two was the initial basis of the study, however this approach to justification proved to be a barrier to adoption (see discussion section).

Current supply models vs proposed model

The current supply model has the Municipality as the sole supplier and biller of energy to the end user. This exposes the end-user to various charges involved in the supply and use of that energy. The primary charge (above the energy cost) being a 22.5%voltage surcharge to step the voltage supply down from 11kVA to a usable 400v. That surcharge is calculated on the total bill (including all network demand charges) this charge is as a result of equipment cost and maintenance. With around 35% of the total energy costs being related to supply charges above actual electricity costs, this is an area that is often overlooked in energy efficiency measures as it does not provide any direct environmental benefit and investment does not provide any production capacity.

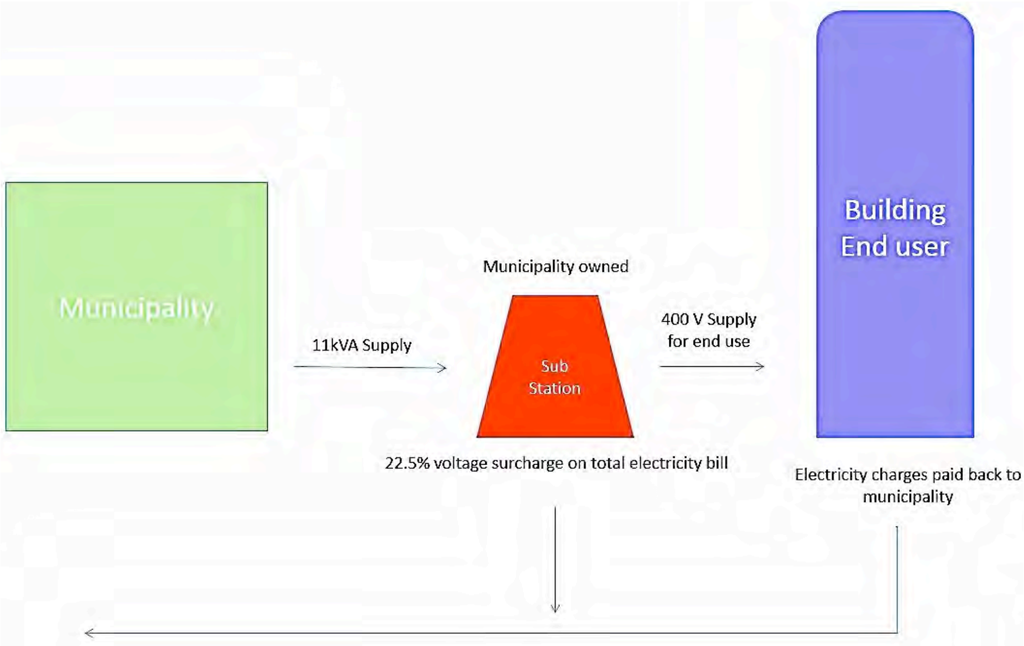

Figure 1 Current grid connection

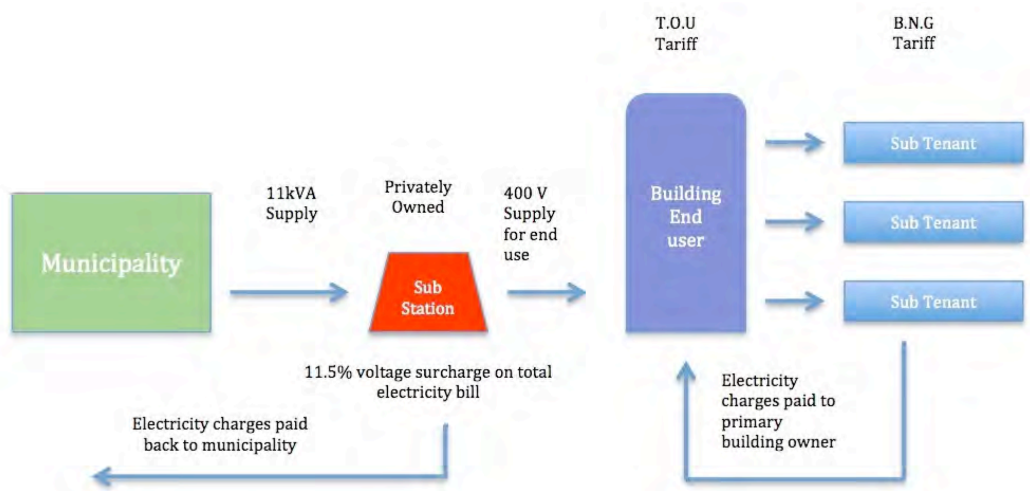

Figure 2

Proposed Model

The new proposed model (as outlined in Fig.2) has the municipality as the bulk supplier, and the end-user as the secondary supplier and provider of energy to the separate sub meters in the building that supply the tenants. This has numerous advantages. First of all, an immediate reduction in monthly electricity bills of 11%, in itself would be sufficient to justify an investment. Secondly, the building owner can actually become a supplier of electricity; this allows the owner to take advantage of the two different pricing structures. Supply is at T.O.U tariff, while sub supply is at B.N.G. This allows the building owner to in essence charge a premium of on average 25c per kWh for the sub meters. Thirdly, the adopted solar plan has the effect of allowing the building owner to take advantage of the lower

T.O.U tariff, while receiving payback from the solar electricity at the higher B.N.G rate. Furthermore, if the owner wished to supply back to the grid he is now able to currently at the same rate that Eskom supplies the local municipality. This provides greater flexibility and predictability for income from a solar retrofit and battery storage adoption, reducing overall risk and increasing the probability of sustainability. The financial potential for renewable adoption in the Microgrid setting is represented in the table 1.

Table 1 Financial potential for renewable energy alternative scenarios

Combined approach discounted payback periods	**Solar**	**Solar and chemical storage**	**Solar, chemical storage and tariff retrofit**	**Chemical storage and tariff retrofit**
Capital costs	1 404 000	3 904 000	4 004 000	2 600 000
Current energy costs	>15 years	5.6 years	3.2 years	2.6 years
12.5% year on year increase in energy costs	7.5 years	3.1 years	2.4 years	2.2 years
CO_2 offset/ year	77tons	77 tons	77tons	77tons
Savings per year (worst case)	114300 5.2%	407000 18.5%	809 000 36.8% savings	490500 22.3%
Financial Risk	Moderate due to nature of investment in renewables	Moderate due to nature of investment in renewables	Low due to short payback periods and the inclusion of renewables	Very Low due to short payback periods and high rate of return on investment
Benefit of investment	Low due to capital tie up versus monthly savings	Moderate due to capital tie up versus monthly savings	Very high, short payback period, significant savings. The investment in renewables ensures long term sustainability	Very high, short payback period, high savings coupled with low capital investment risk

Results and discussion

The use of certified companies for pricing as well as a once-off energy study using measurement devices allowed the quantification of benefits of Microgrid and renewable development on economic grounds. This increased information of economic potential should enable the measures to be a less risky idea for the business, thus enhancing the probability of successful investment returns through the associated reduction in risk. A 2.4-year payback period with a reduction of 36.8% in energy bills will significantly alter the business ability to compete in light of rising energy costs. However, when the proposal was presented to the building owner, the idea was rejected due to the high costs involved (the case study had sufficient and available capital for the investment) on reflection the building owner was presented with another option. The option involved first developing the Microgrid and establishing his individual identity with solar and chemical storage to follow. Through discussion with the owner a conclusion was drawn that the owner lacked sufficient enhanced ability at making economic decisions based on future occurrences. The first option was also representative of the owner "opting in" to renewable plan vs. having to "opt out" of the renewable plan once the Microgrid was established. This lack of decisional ability can be attributed to the bounded rationality of the individual in that while rational, he exhibits cognitive restraints at processing information. Contributing factors are choice overload, innate heuristics, reference points, time varying discount rates and even the phenomenon that individuals are not risk neutral, in that the owner valued losses higher than an equivocal gain. In essence, the current energy climate should then not be viewed as a failure on the part of the person, but instead as a direct consequence of a failure in design. Neoclassical economics found its greatest challenge in *behavioural economics*; a simple example of this bifurcation from traditional views is the puzzle of why people will often risk/damage their long-term future for immediate gratification. Designing a system or developing an energy policy cannot use an individual or social deficiency, as a basis for an explanation of failure. Instead failure can be attributed to an inadequate design, which failed to either address or mitigate the potential for those deficiencies or variations. Hence, designing an energy plan or grid model needs to factor in the macro social relationship dynamics as well micro behavioural characteristics of individual cognitive agents.

Key to this idea is the role that *information* and *interactive learning* play. In fact, in an evolutionary system, learning alters the shape of the search space in which evolution operates and this has the side effect of allowing expedited evolution [11]. Hence facilitating and enhancing this interactive learning is crucial within the new proposed model. Promoting the access to energy information, the potential for an individual identity and the creating of the idea of "opting out" vs. having to "opt in" to energy investment was seen to be the viable method of attaining success.

Conclusion and recommendations

There are two distinct proponents to the outcomes in the form of a social relationship aspect and an economic aspect, hence the term socio-economic system. The rational of this paper was the idea of changing the norm, moving away from neoclassical economic ideals to that of a behavioural based approach, particularly with regards to shifting focus towards psychological, sociological and institutional variables as being determinants of choice [12]. This created a certain degree of realism regarding the case studies (building owner) simplifying assumptions in his decision making process. Further highlighting the idea that individuals incur self-inflicted systematic biases and procedural errors as a result of their decision making process. In neoclassical terms this would imply that the case study has reoccurring irrationality as a consequence of these biases and his cognitive illusions. But why is this focused non-traditional approach viable when it comes to micro and macro-economic outcomes? Namely: infrastructure plays a fundamental role through enabling and governing spatial flow of resources, goods and services. However, there still exists a need to understand how infrastructure systems develop and change within the wider economy, this development is emphasised by the socio-economic change exhibited by the case study. This focus on the interaction between infrastructure, economies and social paradigms creates a form of co-evolution within a complex adaptive socio economic system. This idea of co-evolution of systems within a complex setting highlights the key reasons for this non-traditional focus on decision making behavioural characteristics.

- Assumptions matter, not just for analysis but also for understanding why individuals behave how they do based on their cognitive abilities and environmental constraints.

- Cognitive capacity, cultural learning and the flow of information all have an effect on intelligent decision-making.

Energy use is a form of consumption, representing not just a purchase of goods, but it defines even the time we invest in activities such as work, exercise, social media etc. this consumption produces a history, which has the attribute of maximizing personal welfare. Hence if consumption is too high or too low, how is the case study able to identify that? Thus maximization requires knowing your current consumption rate as well as having the added ability of repeated choice. Implementing behavioural models relies on understanding the problem of individuals who exhibit insufficient self-control, hyperbolic discounting as well as incorrect preference assumptions based on bias and illusions. With utility occurring on an aggregate scale over time while choice occurs at a local scale occasion-occasion [13], thus each choice the case study makes has a direct utility impact as a result of the consumption experience as well as an associated indirect utility effect on future consumption. Individuals often ignore this indirect utility leading to internality, this internality often leads to a consumption rate which when reflected upon is seen to be non-optimal. This may seem trivial, however, when the ignored indirect utility is in fact an externality then these ignored consequences now fall on other individuals. Hence the idea of consumptions and our actions related to consumption of energy and resources is vital in ensuring the true optimal outcome for not just the socioeconomic environment but also the co evolution of the socio-technical environment of infrastructure development.

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"SUSTAINABLE GRID INFRASTRUCTURE: THE CO-EVOLUTION OF SOCIO-ECONOMIC AND SOCIO-TECHNICAL SYSTEMS THROUGH MICROGRID ADOPTION"

D. Hayman[1], C. Loggia*, C. Trois[1]

*Corresponding Author: Dr Claudia Loggia; Telephone: +27(0)312601771;
e-mail: Loggia@ukzn.ac.za
University of KwaZulu-Natal, School of Engineering, Property Development Programme, Howard College campus,
Durban, South Africa

[1]University of KwaZulu-Natal, School of Engineering, Civil Engineering Programme, Howard College campus,
Durban, South Africa

ABSTRACT AND KEYWORDS

PURPOSE OF THIS PAPER: The purpose of this paper is the development of an understanding towards the notion of sustainability, so as to form a basis for challenging the classical operation of the current passive energy system in favour of one which is more dynamic, and adaptive, promoting effectiveness of individuals within the system, vs. pure system efficiency as the driver of sustainability objectives.

DESIGN/METHODOLOGY/APPROACH: The research combines a theoretical approach based on available literature with a case study approach focused on analytical usage data on an existing building, along with a discussion on the aggregated potential of dynamic consumers.

FINDINGS: Microgrid adoption was proven to be viable on technical and economic grounds. A *3.7-year payback* period along with a 36.8% in energy expenditure provides a means for increased renewable adoption and enhanced consumer participation in grid sustainability.

RESEARCH LIMITATIONS/IMPLICATIONS: Due to a limited time frame, theoretical values for production and future tariff increases were used.

PRACTICAL IMPLICATIONS: Adoption of microgrids and renewable energy systems at the micro level affords a more dynamic energy grid with enhanced robustness and sustainability through variety of supply.

WHAT IS ORIGINAL/VALUE OF PAPER: The results are used to provide justification for increased focus on creating *active energy users* through Microgrid adoption, facilitating a change from a vertical to a more horizontal complex grid structure consisting of distributed active consumers.

KEYWORDS: Microgrids, Smart grid, sustainability, Complex systems, Distributed resources

INTRODUCTION

This paper builds on previous research and seeks to answer the fundamental question of whether by taking an individual centric approach, in the form of modularity of individual consumers, through Microgrid adoption, would it be possible as a result to aggregate influence on the operation of the energy system. In fact, another question is related to better fulfil the initial aims for which the system was created, that of providing energy to all parts of the systems in a sustainable manner. It is hoped to question whether sustainability as a *characteristic*, not an *outcome*, can emerge from the system and if so, how is it possible to ensure that this emergence continually tends towards sustainability for generations to come even when placed under systematic stress by external and internal variations. Introducing distributed energy sources is vital in ensuring system robustness in the long term, however this introduces variations into the system which previously were not designed for, and if left unchecked has the ability to reduce overall effectiveness of the system as a whole even in light of a scenario where individual agents become increasingly more efficient and sustainable.

No longer we are able to exist in isolation, our daily lives and our existence is a function of our immediate actions and our environment primarily consisting of those we are connected to, known and unknown, these relationships within a system hold the key to creating an adaptive effective system, able to harness our increasing efficiency and as a consequence allow sustainability to emerge. The idea of complexity hinges around the whole resisting reductionism [1], in that its parts are unable to be studied in isolation. For the sake of this paper, the focus is on how it is possible to quantifiable facilitate and integrate individual actors within the system in order to induce complex properties and adaptions.

Using Agent based modelling principles and theory, it is hoped that a discussion on what is possible will stimulate thoughts on our current system. An in-depth generation of a working model is beyond the scope of this paper; however, this paper will serve as a stepping point to further studies and discussion on more in-depth real world complex scenarios. In Systems theory the patchiness principle refers to the notion that system instability is as a result of a systematic lack of capacity to use a variety of resources [2]. Our current rigidly centralised hierarchical system is that exact inability which the patchiness principle refers to, as Richardson's neatly sums up " *… to maintain a level of stability in the face of changing conditions a system should not invest too much time and effort into one particular way* *of doing things"* [3]. A capacity to take advantage of a plurality of resources allows the system to "move with the times". Our inability to transition from our current mind-set of being purely energy consumers with a right to energy, to that of being *active participants* in the supply in the form of prosumers, will inhibit transition to a grid structure which is more resilient to negative events and will fundamentally inhibit the effectiveness of renewable energy production and as a consequence the achievement of a sustainability in the long term.

BACKGROUND

If we succeed in creating sustainably effective individual consumers through Microgrid adoption, we would have only partially realised the true potential of intelligent individuals and their role within the newly created systems. If these intelligent agents are structured within an intelligent network, so that there is autonomous interaction with upper levels (vertical and horizontal) of the hierarchical energy system, as well as with the connected consumers, then this intelligent network has the characteristic ability for being amongst others: *self -supporting*, *adaptive*, *active*, *cost-effective*, *eco-friendly* but, above all, *secure* and *stable*. This final part of this investigation deals with theoretically creating a horizontal structure within the energy grid, where an enhanced consumer plays a central role. The justification for a more horizontal grid structure is as a result of the substantial aggregation effect of building consumption, and in theory the potential energy production potential inherent within the horizontal structure in the form of an aggregation of individual building energy production and savings. This horizontal structure is the corner stone of an intelligent/smart grid; however this system is one system within the confines of a "*system of systems*" from the weather system which impacts the energy system, to the social behaviour of the individual interacting with the energy system creating emergent challenges which need to be accounted for when designing or restructuring the energy system for the future. This redesign in the form of horizontal structure creates an increase level of complexity that, when embraced, has the potential to enable sustainability to emerge [4].

RESEARCH CRITERIA AND METHODOLOGICAL APPROACH

This paper is aimed at critically analysing the existing vertical model towards energy supply and sustainability through a theoretical approach based on the current literature review and a conceptual case study developed in Durban (South Africa). Formulating the framework for which a complex multi-agent and horizontal model can be adopted through the establishment of modular microgrids, embracing the inherently dynamic environment in which energy supply and subsequent use exists within. The literature review in the research phase dealt with providing an alternative through the development of a complex system characteristic, embracing behavioural characteristics and traditional economic principles, cultivating coordination within the framework of a higher knowledge base allows for previously segregated and isolated agents to effectively contribute to their own sustainability, as well as the collectives through their enhanced participation in grid security and supply. This knowledge was incorporated into the case study and was used to provide justification for Microgrid adoption through consultation with eThekwini electricity. Moreover, relevant renewables resources in the form of Solar PV, was adopted due to its flexibility and ability to be installed in incremental capacities and in modules. Building energy Data was captured by installing (temporarily) a meter to execute an energy audit. The findings were then correlated and aggregated through theoretical discussion on multiple system adoptions across a broad range of similar buildings, particularly with a focus on the ability to replace traditional centralised supply with distributed resources, facilitated by private individual consumers, who have been granted an enhanced role in grid supply though increased autonomy and individual responsibility.

THE CASE STUDY: ONE SYSTEM MAKING A DIFFERENCE, EVOLUTION OF THE "*DURBAN POWER GRID"*

Why is there a need for developing microgrids? The answer was found lying in two specific areas most applicable to the average building user. (1) Economic and (2) Behavioural. The architecture of a system as Whitney (2006) highlighted, has the ability to either determine or influence the behaviour and property of system [5]. Adopting microgrids alters the structure and, thus, the dynamics of the Microgrid system itself and by extension the broader interconnected systems.

Economic justification

The current supply model existing in Durban, has the municipality as the sole supplier and biller of energy to the end user. This exposes the end-user to various charges involved in the supply and use of that energy. The primary charge (above the energy cost) being a 22.5% voltage surcharge to step the voltage supply down from 11kVA to a usable 400v. That surcharge is calculated on the total bill (including all network demand charges) this charge is as a result of equipment cost and maintenance. With around 35% of the total energy costs being related to supply charges above actual electricity costs, this is an area that is often overlooked in energy efficiency measures as it does not provide any direct environmental benefit and investment does not provide any production capacity.

Figure 1 Current grid connection

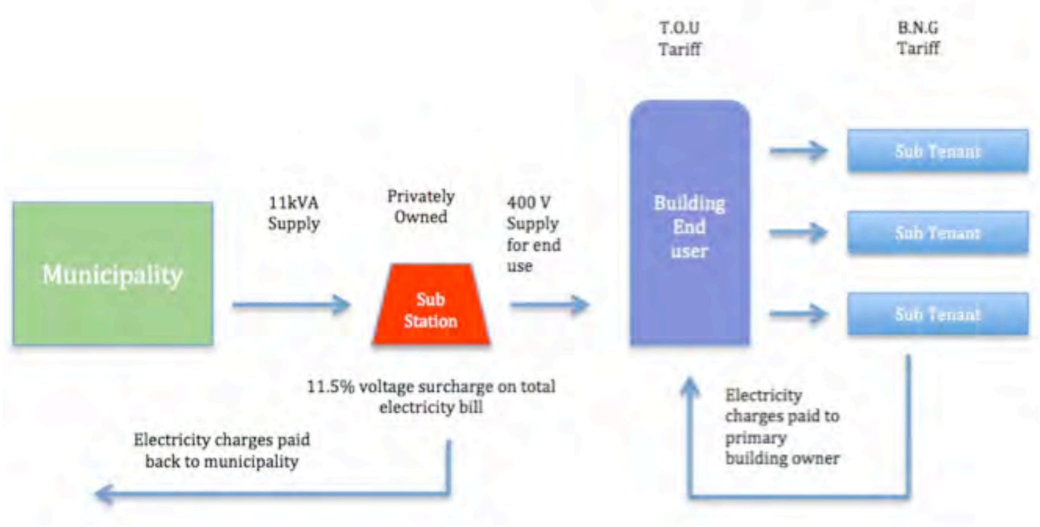

Figure 2 Proposed Model

The new proposed model (as outlined in fig 2) has the municipality as the bulk supplier, and the end-user as the secondary supplier and provider of energy to the separate sub meters in the building that supply the tenants. This has numerous advantages. First of all, an immediate reduction in monthly electricity bills of 12%, in itself would be sufficient to justify an investment. Secondly, the building owner can actually become a supplier of electricity; this allows the owner to take advantage of the two different pricing structures. Supply is at T.O.U tariff, while sub supply is at B.N.G. This allows the building owner to in essence charge a premium of on average 25c per kWh for the sub meters. Thirdly, the adopted solar plan has the effect of allowing the building owner to take advantage of the lower T.O.U tariff, while receiving payback from the solar electricity at the higher B.N.G rate. This provides greater flexibility and predictability for income form a solar retrofit and battery storage adoption, reducing overall risk and increasing the probability of sustainability.

Voltage Surchage

Voltage	%Surcharge
275 kV	0.00
132 kV	2,25
33 kV	3,00
11 kV	10,50
6,6 kV	12,75
400 V	22,50

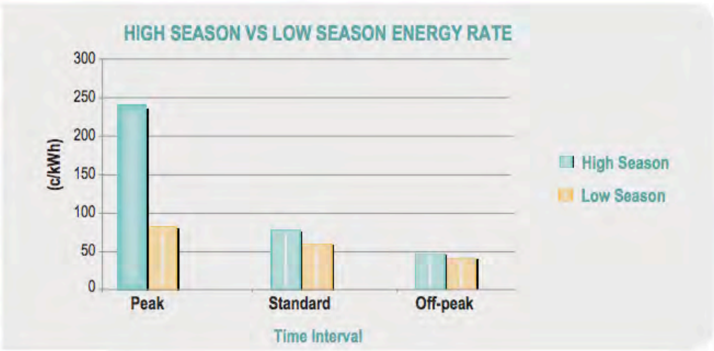

Figure 3 Voltage surcharge [6]

With Local grid supply is via a distribution ring at 11KV. Accessing the 11KV distribution ring is reliant on the establishment of a Microgrid through the installation of a mini transformer with 11KV feed. This would, in effect, mean the building has the potential to exist as an island from the main grid in case of a system failure or if the client wished to develop a fully self-supporting system. Currently, the economic benefits of microgrids adaption are deemed the most crucial as a means of providing greater feasibility for a RES system to be developed on site.

There are two components to this, if we use off-peak to charge the BESS system the energy cost is in effect 12% lower, while when we sell it (by using it at Peak periods) the energy savings are 12% higher. This is summed up below in table 1 for the system as a functioning whole.

Behavioural Justification

Security is crucial component of investment in renewable technology, by establishing the building, as a Microgrid the energy environment is partially segregated from the broader general energy environment. A Microgrid system creates a system, which is definable and has a greater degree of control then a system integrated into the broader grid system. This increased security and definable boundaries means that in the climate of current shortfalls and sustainability calls, the segregated system of a microgrids has the ability to produce, off-set and account for their individual energy system. It is this accountability, which provides the self-motivation for investing in a sustainable solution to an individual's energy system that is not solely reliant on traditional means of supply.

The results for the investigation were mixed and varied; at the beginning of the investigation the objective was to create a user that was more effective and in effect sustainable. If these are rigid objectives then either a production or storage system structure alone are not enough to satisfy the definition of sustainability.

It was found that achieving sustainability relied on a combined approach with the aggregation of the outcomes tending towards a system which is both sustainable and cost effective so as not to drive away investment potential. Table 1 below, summaries the secondary financial component of sustainability.

Table 1 Combined financial results of investigation

Savings from solar		1	2	3	4	5	6	7	8	9	10
Energy Saved		52175	55762	59596	63693	68072	72752	77753	83099	88812	94918
Tax cost due to savings	28%	-14609	-15613	-16687	-17834	-19060	-20370	-21771	-23268	-24867	-26577
	Total	37566	40149	42909	45859	49012	52381	55982	59831	63945	68341
BESS	ITOU rates	1	2	3	4	5	6	7	8	9	10
Arbritage		133873	150607	169433	190612	214438	241243	271398	305323	343488	386424
Demand savings (R)	R76,40	77011	86638	97467	109651	123357	138777	156124	175639	197594	222293
Notified demand savings (R)	R24,13	24323	27363	30784	34632	38961	43831	49310	55473	62408	70209
Tax	28%	-65858	-74090	-83351	-93770	-105492	-118678	-133513	-150202	-168977	-190099
Total		169349	190518	214332	241124	271264	305172	343319	386234	434513	488827
Voltage savings		228000	256500	288562,5	324632,813	365211,914	410863,403	462221,329	519998,995	584998,869	658123,728
Cash flow Projections		1	2	3	4	5	6	7	8	9	10
Combined income		434915	487166	545804	611616	685488	768417	861523	966064	1083456	1215292
Vat Claim		424000	0	0	0	0	0	0	0	0	0
Depreciation		448000	268800	179200	0	0	0	0	0	0	0
Total	-2900000	1306915	755966	725004	611616	685488	768417	861523	966064	1083456	1215292
Cash Flow	-3200000	-1893085	-1137119	-412115	199500	884988	1653405	2514928	3480992	4564448	5779740
Year			2	3	4	5	6	7	8	9	10
Payback Period	3,7 Years										
IRR	28%	See Apendix									
ROI (nominal)	144%	See Apendix									

If we succeed in creating sustainably effective individual consumers through Microgrid adoption, we would have only partially realised the true potential of intelligent individuals and their newly created systems. If these intelligent agents are structured within an intelligent network, so that there is autonomous interaction with upper levels (vertical and horizontal) of the hierarchical energy system as well as with the connected consumers, then this intelligent network has the characteristic ability for being amongst others: *self-supporting, adaptive, active, cost effective, eco-friendly* and above all *secure* and *stable*. This final part of the paper deals with theoretically creating a horizontal structure within the energy grid, where the consumer plays a more central role. The justification for a more Horizontal grid structure is as a result of the substantial aggregation of building consumption, and in theory the potential energy production potential inherent within the Horizontal structure in the form of an aggregation of buildings. This Horizontal structure is the corner stone of an intelligent/smart grid, however this system is one system within the confines of a "*system of systems*" from the weather system which impacts the energy system, to the social behaviour of the individual interacting with the energy system creating emergent challenges which need to be accounted for when designing or restructuring the energy system for the future. This redesign creates an increase level of complexity that, when embraced, has the potential to enable sustainability to emerge [7].

Replicating a distributed Power plant

Is it possible to create a distributed renewable energy plant, comparable to a traditional centralised fossil fuel based plant? And if so, what exactly would it take to reproduce the production potential of a coal fired powered plant using distributed RES? And is it feasible that a virtual (virtual by nature of its separated components) renewable power plant could be a replacement for a traditional centralised power plant?

As the fourth largest coal fired power plant in the world when completed, Kusile is an ideal benchmark for comparison. Ideal due to its nature and reliance on fossil fuel for energy production, its nature as a centralised production method which is reliable in its output, yet inflexible in the nature of supply. With currents plans to build a similar size coal fired plant called “coal 3” there is a benchmark to which a RES could be justifiably compared and promoted as a viable alternative to what arguably is an outdated technology which contributes large volumes of harmful Greenhouse gases to our environment.

At 16% of total Eskom supply capacity, Kusile is a large component of our power system, with a correspondingly large negative environmental impact. Large transmission distance also equate to transmission losses of around 10% for distance > 600km from the plant itself.

The main benefits of renewable production:

6. No continual input cost to produce energy after initial capital cost and some minor maintenance costs;
7. Production occurs closer to demand resulting in less transmission losses;
8. A RES system allows for supply to match demand resulting in less off-peak wastage;
9. A RES system evenly distributes peak load reducing infrastructure requirements;
10. Sustainability is achievable as renewable resources are non-diminishing and produce zero carbon during production.

Table 2 Kusile coal power plant statistic

Size	**4800 MW**
Cost	**118 000 million**
Actual cost if operating costs included	**282 000 million**

Life span	**60 years**
CO2 produced per annum	**37 Million ton**
Coal used per annum	**17 Million tons**
Downtime	**10%**
Average annual production	**37900GWh**
% Of Eskom annual production	**16%**
Fuel, operation and maintenance costs	**25%**
WACC of 8% over 30 years	
Average cost/Kwh produced	**R1, 45**

Table 3 RES cost for Kusile sized supply

Required output	37000	GWH
Solar case study system	0,0816	1 Building
Systems to match Kusile	453432	
Cost per system	2100000	
Total cost	950	Billion

With a life span of 60 years, Kusile will be around for an extended period of time, requiring unsustainable and environmentally harmful practices to fuel the process due to its reliance on fossil fuel inputs. When compared to this a RES at R950 Billion, may sound beyond the reach of even a comparison, particularly when the system is only guaranteed to last a period of time which is far shorter than a large coal fired plant. However, if one considers the fundamental differentiate between the two in the form of the externalities placed on society through the technology, weighting the costs, while not entirely quantifiable, are justifiable.

Table 4 Estimated annual externality cost Kusile [8]

	Net output	Externality cost			
	GWh	Low (R million)	R/kWh (Low)	High (R million)	R/kWh (High)
Health	32 301	182.8	0.006	213.3	0.007
Climate change	32 301	3 148	0.097	5 334	0.165
Water	32 301	21 305	0.660	42 357	1.311
Mining	32 301	6 538	0.202	12 690	0.393
Total		**31 174**	**0.97**	**60 594**	**1.88**
Total excluding water for generation purposes*		**9 869**	**0.31**	**18 237**	**0.56**

A case study by Greenpeace generated the following cost of externalities, assuming the same 25 year period as solar feasibly will last, the results shift slightly closer.

Assuming the lower calculated externality cost over 20 year the societal cost would equate to 700 Billion Rand, if transmission losses are ignored but the operating, running and input costs are included, over 20 years. The actual cost of Kusile is in the region of R863 Billion, far closer to the R950 Billion required to construct a theoretical RES of comparable size able to replace Kusile. Another often ignored consideration is the direct foreign financing received for Kusile from foreign banks and investors. This investment is not-altruistic and thus requires an interest rate included in the repayments. Over 30 Years on a loan of the size taken for Kusile, the interest payment would equate to around R166 Billion rand at an assumed 8%. This in effect brings the total cost of Kusile, if repaid over 20 years, closer in the region of R974 Billion Rand, slightly above the R950 Billion a RES would cost.

While the financial justification for RES is evident, if one is to go beyond just the numbers involved, then the true potential of a distributed RES becomes evident. It is how the system is constructed that holds the greatest potential. Responsibility for construction is deferred from as single controlling entity to that of 450 000+ individual direct consumers, meaning risk is spread amongst a far greater percentage of the energy users demographic. It is this modularity and flexibility in adoption which means the total investment input is now correspondingly lower resulting in increased adoption rates and greater value for money in the long term. Sustainability being an inherently social issue is now, thus, solvable directly through a social mechanism and instead is not reliant on a centralised system driven intervention with only indirect links to the social cause of the issue.

Results and discussion

Recreating a traditional coal power plant through RES is reliant on a financial input far greater then what is feasibly possible through a single source of intervention, however when that financial cost is spread amongst the collective, and is provided by private individuals, then the goal for renewable adoption is infinitely more attainable with the collective benefiting as a whole, through a more secure and diverse grid supply which has increasing levels of sustainability [9]. Going forward there are four areas of focus, which a particular focus is needed from a municipal point of view in order to drive adoption. Policy needs an increased focus on not just the technical but also the cognitive disposition [10] of individual consumers in the form of:

1. Increased use of a loss aversion framework. Humans are intrinsically loss averse, thus users need to be more aware of their usage and when they use energy. This is reliant on real time data and a direct link to the consequences of energy use. Merely using a TOU tariff is ineffective when the consumer assumes there is no other option. To this end based on earlier discussions of behavioural characteristics a change from post-paid TOU to prepaid TOU would enhance the loss aversion affect for the consumer as there is a direct relationship to how they consume energy. This would be facilitated through the adoption of Microgrid with enhanced grid communication in the form of real time data.
2. Opt out, not in. Sustainability will fail, if consumers in the system are able to benefit through ignoring calls, which negatively impact the individual while benefiting the collective. Game theoretic principles proved that the rational choice in the situation is selfishness in favour of personal gain. In the current grid set up this was proved to be the correct decision even with the resulting consequences being a failure in the system. Altering this is reliant on creating a system or policy, which can only be opted out of, and not merely be a system where there is a request for opting in. In effect, sustainability and renewable technology become the default option and not merely the preferred and often ignored option this theory is based on numerous studies where altering the default option greatly increased adoption rates for an option which

was previously ignored.

3. Discount rates for Renewable and distributed resources need to be reduced. High costs for Solar PV will always be a barrier to wide spread rapid adoption; this requires a concerted focus on methods or mechanisms able to reduce this factor. As discussed earlier a small increase in buy back prices as well as tax incentives could address this. However more is needed to reduce pay back periods and thus the risk of investment further. A viable option would be incorporation of the cost into building repayments or utility repayments, helping spread the original upfront cost of the system over a period of time. This, however, is reliant on government invest which perhaps is not currently available
4. Effective design. The future energy system structure needs to be design from the perspective of the user. This includes not just the technology but the policies and mechanisms used to drive adoption of RES. Simplifying and streamlining the adoption process will make the new RES systems inherently more user friendly and decrease the consumers aversion based on pure confusion and non-clarity. Through reducing the number of factors needed to take into consideration as well as allowing more functional information to be able for the consumer to process. This has the antithesis of an increase complexity in designing the system to make it operate effectively, however the modular nature of microgrids and Distributed resources means this complexity is easily managed and an advantage in a vulnerable energy system.

By providing consumers with a platform to contribute to their own energy security, the potential aggregated consequence is improved grid security for the collective as well a system which coverts effectiveness rather than one which relies on rational consumers to be more efficient at a direct cost to themselves. A system with multiple agents acting within a hierarchy that exhibits increased horizontal and not vertical structure through multiple distributed energy sources will lead to a grid which is inherently sustainable and robust [11], one which is able to meet not just our current needs, but our needs in the future.

Conclusion and recommendations

Microgrid development was proven to be justifiable on economic grounds, reducing payback periods while providing an income potential previously not evident. This increased economic potential enables sustainability measures to be a less risky proposition for business thus enhancing the probability of success through the associated reduction in risk. A 3.7-year payback period with a reduction of 36.8% in energy bills will significantly alter the business ability to compete in light of rising energy costs in the short term this reduction of risk and decrease in payback periods can provide justification for future adoption of increased renewable production. This adoption will enable a new enhanced level of knowledge to develop within the grid and its users. This will have a corresponding increased adoption rate of RES, resulting in the single agent system with its vertical hierarchical structure being replaced with a multi agent system, which has a more horizontal and distributed structure with greater variety in supply as well as an enhanced system robustness. This reduces sustainability's success to a sum of its parts versus being reliant on the whole allowing the principle of emergence to drive sustainability in a more open and dynamic system. By providing the individual with an identity, enhanced sustainability thinking was promoted, in that actions now have direct and measurable consequences for one self as these actions not incrementally diminished or altered by the collective inaction.

Microgrid potential is clearly evident for an individual or business. However, this benefit can be extended to the collective if accurate and real-time data is used to coordinate energy usage and renewable production. Allowing seamless energy export to the grid at a higher net rate then is currently afforded will further enhance the viability for renewable production promoting higher levels of investment in renewable generation and storage. This production can be used to supplement current supply deficiencies or in the long run can be used to replace the need for further non-renewable production means. This decentralised approach allows energy produced to be consumed in the same spatial frame, enhancing efficiency further as well as providing further incentive and control for municipalities to safe guard themselves against future shortfalls in supply. Above pure efficiency, a decentralised distributed system consisting of multiple sources creates a system which is highly effective and by extension sustainable.

Future studies need to focus on creating *Microgrid communities* where interests are aligned in such a way that renewable production and storage are optimised, allowing the Microgrid to exist solely using off-peak grid power while being a net energy producer in peak periods. This approach will provide energy security and financial risk reduction for the individual as well as allowing sustainability goals being achieved via a combination of individuals benefiting the collective as a whole, thus accelerating sustainability success through the use of multiple agents' actions with society being the solution to one of their greatest needs.

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