ENERGYSHED FRAMEWORK: DEFINING AND DESIGNING THE FUNDAMENTAL LAND UNIT OF RENEWABLE ENERGY

by

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DEDICATION PAGE

This work is dedicated to our children.
May we choose wisely for their sake.

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ABSTRACT

Renewable energy systems are fundamentally different than fossil-carbon energy systems, with each having a unique set of constraints, performance characteristics, and impacts. Transition to a new primary energy resource has significant restructuring implications for human systems and their impacts on environmental systems. It is not reasonable to assume that renewable energy systems should be structured in the existing pattern of fossil-carbon systems. The energyshed concept is proposed as an organizing framework for renewable energy and related supporting systems, with focus at the city level and based upon the unique characteristics of renewables. The fundamental land unit of renewable energy is proposed as a contiguous area of land that is power-balanced. This land unit is conveniently relatable to other land-based constructs such as watersheds, ecological units, or urban development patterns for identification and analysis of coupling and land-use conflict. The concept draws from a broad swath of physical and social science fields. The framework is developed through exploration of definition, values, principles of design, discussion of cartographic tools for model development and a discussion of expected structure and behaviors of an energyshed. The energyshed concept fills an important vacancy for a robust organizing framework for renewable energy systems and is applicable to scientists, engineers, planners, and developers related to the field. The recommendations in the last chapter serve appropriately as stand-alone policy tenets for a municipal energy plan or within the context of adoption of the energyshed framework en masse.

LIST OF ABBREVIATIONS AND SYMBOLS USED

CAES	Compressed air energy storage
DEM	Digital elevation model
DPSM	Digital power surface model
DTM	Digital terrain model
EIA	Energy Information Administration (United States Dept. of Energy)
GIS	Geographic information system
GPP	Gross primary productivity
HANPP	Human appropriated net primary productivity
IEA	International Energy Agency (of the OECD)
LiDAR	Light detection and ranging
NPC	Net power capacity
NPP	Net primary productivity
NREL	National Renewable Energy Laboratory
OECD	Organization of Economic Co-operation and Development
P_{pp}	Power production potential
P_D	Power demand
RET	Renewable energy technology
SI	International System
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Program
UNFAO	United Nations Food and Agriculture Organization
UNIPCC	United Nations International Panel on Climate Change
USDA	United States Department of Agriculture
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency

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CHAPTER 1. INTRODUCTION

Renewable energy systems are fundamentally different than fossil-fuel-energy systems and so energy systems and their planning must evolve with the change of energy resource (Scheer, 2002; Smil, 2008). Whereas fossil-fuel-energy systems are constrained by atmospheric pollution in the near term and supply in the longer term, renewables have neither of those constraints (UNIPCC, 2007; Tester, Drake, Driscoll, Golay, and Peters, 2005; Johansson, Kelly, Reddy, Williams, and Burnham, 1993; Smil, 2003). Alternatively, the employment of renewable energy technology (RET) is a land-use issue fraught with potential conflict with other critical land-uses such as agriculture, water, and biodiversity (Smil, 2008; Gautier, McCabe, Ogden, and Demayo, 2010). Energy infrastructure is central to the function of a city and yet is often a planning after-thought rather than an intentional design to the urban form (St. Denis and Parker, 2009). Transition of the dominant energy resource from fossil fuels to RET is a fundamental change not just in the energy system but the entire social system that it supports. Incrementalism is a potential default approach to energy transition. Each incremental step alters the possible future trajectories of the system, known as path dependency, to which complex systems are particularly sensitive. Therefore incrementally building the renewable energy system into the image of the fossil fuel system is to do so without critically considering what the next generation of energy systems ought to be, based on its physical properties. Doing so is to drive blindly with no control of the trajectory.

This monograph presents the energyshed, a conceptual framework, to structure ideas of how renewable energy might be organized and to guide city-level energy planning in practical application. I chose not to discuss some of the traditionally emphasized topics of energy such as energy markets, economic expediency, and entrenched geo-political structures, which are not elements of an energy system but rather the emergent results of the dissipation of energy (Annila and Salthe, 2009).

Instead I will present a perspective of the physical process of solar-based energy that is significantly interconnected to land and its transformation. It is land that is the integrator for connecting many vital systems, and so the shed appeals as a fundamental unit of organization and analysis for energy.

The monograph's central research question of how the broader renewable energy system might be organized is addressed by proposing the shed as the fundamental land unit of energy organization and analysis. Development of the concept of energy, the fundamental unit, and a succinct and inclusive definition for the energyshed support the exploration of the central research question. How might the design of an energyshed be guided? The field of resource management informed the decision to advance a concise set of energy-related values and design principles that provide further detail to the application of the energyshed definition. How might analysis of the energyshed be conducted? The field of energy cartography, bolstered by accumulation of remote-sensing data and advances in geographical information systems (GIS), has made great advances in the past decade (Howell and Baylis, 2014, Jakubiec and Reinhart, 2013; Calvert, Pearce, and Mabee, 2013; Lopez, Roberts, Heimiller, Blair, and Porro, 2012). Yet, no discipline has to date developed a suitable method for integrating renewable energy in such a way as to support development of an organizing structure such as the energyshed. The digital power surface model (DPSM) is proposed as an integrated surface for determining boundaries and energy transfer within. Finally, what sort of structure and behaviors might be expected from an energyshed? Structure and behavior are both derived from the components of the system (Sterman, 2000; Meadows, 2008) and so those components are defined and described early in the monograph. Developing a reasonable understanding of the behaviors and specific structure within a practical energyshed will require dedicated modeling and analysis. I have explored several structural elements that I expect will be present in a practical energyshed by extrapolating concepts from the fields of ecology, complexity, and the thermodynamics of non-equilibrium systems, all of which share an organizing theme of energy dissipation.

The chapters of the monograph are organized to explore primary dimensions of the energyshed with the ultimate goal of leaving the reader with a sound sense for the form and function of the concept, and maybe just a hint of the utility and beauty of what could be by releasing the constraints of what currently is (Robinson, 1982; Schwartz, 1996). Those dimensions are: definition, components, values, principles of design, mapping, and structure. Definition describes energy, which is far more complex and abundant than the passé idea of energy as simply a commodity. The role of both fundamental units and land units are explored as a taxonomy for the definition of the energyshed. To understand an open system requires exploration of the levels above and below it, so eight internal components are examined. The values and design principles dimensions are employed to develop some sense of context for the energyshed for the broader community within which the energyshed is situated. I suggest reasonable and sound values and principles for design, and the logical conclusion of their application would be transformative to many contemporary energy systems, suggesting that the values and design principles currently applied in practice need revisit. Mapping is a principal method used for estimating technical potential for RET employment, as well as identification and analysis associated with shed and land unit delineation. Mapping, powered by GIS, high-speed computing, and remote sensing data, is the analytical link between energy and land. The final chapter, energyshed structure, explores some of the key features and behaviors expected from an energyshed, and suggests that the mathematical techniques of fractals can be applied to energyshed metrics as limiting ideals for design, benchmarking, and performance indicators.

The intention of the energyshed framework is to support facilitation of more-aggressive employment of RET and organization for the structures of and around those renewable energy systems. As such, the primary intended audience is energy planners and researchers, local governments, and energy technology developers. Local government as used here refers to local full-service governments such as cities, municipalities, and townships, or could even apply to villages; city and municipality are used within this document and without distinction. Additionally, for containment and clarity and since electrification is the trend in energy systems, the discussion gravitates to electricity as opposed to heat or solid and liquid fuels, although the general ideas and techniques are applicable to these energy carriers as well.

CHAPTER 2. ENERGY AND THE ENERGYSHED

> *It is important to realize that in physics today, we have no knowledge of what energy is. We do not have a picture that energy comes in little blobs of a definite amount. It is not that way. However, there are formulas for calculating some numerical quantity, and when we add it together it gives...always the same number. It is an abstract thing in that it does not tell us the mechanism or the reasons for the various formulas (Feynman et al., 1963, p.4-2).*

2.1 Nature of energy

Concordant with Richard Feynman's description of energy above, the current understanding of the nature of energy is immature and so too maybe are the associated energy systems of modern times awaiting the next maturation of content and organization. The earliest concept of energy is attributed to the Greek philosopher of "flux and fire" Heraclitus who as early as circa 500 BCE described fire as the source of action and the originator of life (Arnopoulos, 2005, p.21). The term energy is derived from Aristotle's concatenation of the Greek words *en* and *ergon* to form *energeia* meaning "activity of tending toward or enacting a goal" (Energy [Def. 1], n.d.) Aristotle's energeia embraced the "totality of the transitory process, the shift from the potential to the actual" (Smil, 2008, p2).

In modern times, energy is often more narrowly defined as the capacity to produce work (for example Halliday and Resnick, 1981). Max Planck (1945, p41) defined, "The energy of a system is, therefore, sometimes briefly denoted as the faculty to produce external effects." The Energy Information Administration (EIA) of the United States defines energy very practically as, "The capacity for doing work as measured by the capability of doing work (potential energy) or the conversion of this capability to motion (kinetic energy)," placing strong emphasis on heat and mechanical energy (Energy [Def. 2], n.d.). Interestingly the EIA follows in the definition with, "Most of the world's convertible energy comes from fossil fuels that are burned to produce heat that is then used as a transfer medium to mechanical or other means in order to accomplish tasks," elucidating a dominant developed-world paradigm for energy (Energy [Def. 2], n.d.). The field of classic thermodynamics focuses on this gainful relationship of heat and work (Carter, 2001). Even given the refined understanding of heat and work produced by thermodynamics, Smil (2008, p.x) laments the "inadequate integration and insufficient understanding of the complex wholes" of energy in nature and society. Energy has many forms: gravitational, kinetic, heat, elastic, electrical, radiant, mass, chemical, and nuclear (Feynman et al., 1963). However, many of these forms can be collapsed to more fundamental forms, for example heat as kinetic energy at an atomic level. The field of energetics, which is the study of energy flow and transformation across all scales and scientific disciplines, provides a broader definition of energy as, "the ability to transform a system, a process that can involve any kind of energy" (Smil, 2008, p.12-13).

Energy is an abstract purely mathematical quantity describing the state of a system; although it is not an object that permits discrete counting, as other such conserved quantities like electrical charge, energy has several interesting characteristics through which to account for it and build understanding of it (Feynman, 1967). Energy is a conserved quantity, as described by the law of conservation of energy and the first law of thermodynamics, remaining constant through any processes and never consumed, only transformed (Halliday and Resnick, 1981). According to the theory of relativity, this accounting must be met locally, in the frame of reference in which measurement is conducted (Feynman, 1967). "In order to arrive at a definite numerical expression for the energy of the system in a given state, it is necessary to fix upon a certain normal arbitrarily selected state" (Planck, 1945, p41). Frame of reference is an important concept as energy is measured from a given frame of reference, most conveniently a change in energy as a system changes from one state, composition, or configuration to another under the influence of unbalanced force (Feynman et al. 1963; Benenson et al., 2006). The International System (SI) unit for energy is the joule, also the unit of work, which indicates the amount of work performed by or added to a body or system. Feynman suggests that only one unit for energy should be the standard and not the myriad of energy units derived from each individual form of energy (Feynman, 1967).

Energy does not have a "smallest unit", not even at the discrete level of the photon; the energy of the photon is "quantized" according to frequency, but electromagnetic frequency is a continuous spectrum, per the equation energy is equal to Planck's constant multiplied by the frequency of the electromagnetic radiation (Feynman et al, 1963). Smil (2008) proposes that a unifying metric for the many forms of energy is power density of W/m^2, power per unit area. Energy, given its interconvertibility with mass, creates a field, the gravitational field (Feynman, 1967). Energy is the characterization of the state of a body and change of that state, i.e. change of configuration (Beneson, Harris, Stocker, and Lutz, 2006; Smil, 2008). Configuration is a determinant of the energy potential available for use, for which gravitational potential provides the clearest example (e.g. a weight suspended a metre above the floor has potential energy due to its configuration above the floor and in the gravitational field).

Heat energy is a special case of energy, with its own devoted field of science, thermodynamics. All other forms of energy can be converted fully into heat energy but a quantity of heat cannot be fully converted to other forms of energy such as kinetic or chemical (Beneson et al., 2006; Carter, 2001). The second law of thermodynamics describes this phenomenon of irreversibility and upholds the law of conservation of energy with the introduction of the concept of entropy as a form of energy. Entropy is the portion of energy that due to disorder of configuration or state is not available for the extraction of work (Feynman et al., 1963). Entropy is an absolute value by the Nernst heat theorem and the third law of thermodynamics, and perpetually increases in the universe as exergy decreases with every real process (Feynman, 1963).

The thermodynamics of far-from-equilibrium open systems, referred herein as non-equilibrium systems, suggests that some systems, living organisms among them, use an external available flow of energy to increase internal order and structure (Prigogine, 1968; Nicolis and Prigogine, 1977). Internal entropy then is reduced, and external entropy is increased according to the second law of thermodynamics (Prigogine, 1968). Life processes tend toward the path away from equilibrium, which results in the most ordered structure internally and therefore minimum internal entropy (Jørgensen, 2004). Jørgensen (1999) proposes this theory as the fourth law of thermodynamics. Additionally, organisms tend to seek the metabolic pathway that produces the greatest power, which is not typically the most efficient use of available energy; typical organismal metabolic efficiency is around 20% (Smil, 2008). By placing the human and societal organization inside the ecosystem and then applying non-equilibrium thermodynamics as has been applied to ecosystems (Jørgensen, 2004) a more fundamental analysis of human energy systems is permitted, momentarily free of the trappings of abstracted financial calculus. Whereas currency is not physically bounded in global markets, identifying an appropriate boundary for the fundamental unit of analysis of the energy system is a basal requirement in working with the physical phenomena.

2.2 The fundamental land unit of energy

2.2.1 Fundamental unit

Inherent in the definition of fundamental resides the idea of origination and basis for ensuing essential structure and function (Fundamental [Def.], n.d.). It is the starting point from which all ensuing logic is derived. Similarly, the fundamental unit is defined as, "Each of a set of unrelated units of measurement, which are arbitrarily defined from which other units are derived" (Fundamental unit [Def.], n.d.). The existence of fundamental units permits precision, repeatability, and objectivity in analysis (Fundamental unit [Def.], n.d.). In the SI system the seven dimensionally independent units are: the metre, the kilogram, the second, the ampere, the kelvin, the mole, and the candela (Bureau International des Poids et Mesures. n.d.). All of the fundamental units are present in other energy-related units.

The utility of the fundamental unit extends beyond physics and is applied more broadly in other branches of science and government. For example, the ecosystem is considered the fundamental unit of ecology as it is the smallest coherently functioning whole, or system, which includes at the least biota, the relationships and exchanges between them, and the environment with which they interact (Tansley, 1935). The ecosystem thus serves as a primary unit of analysis and research for the field of ecology. Evolutionary biology offers another example. Darwin's (1859) concepts of evolution considered a species to be the fundamental unit of evolution and this was the predominant view on which evolutionary biology sustained itself for nearly a century and half. Advances in genetics have permitted new challenge to Darwin's notion, with recent argument displacing the pre-eminence of the species with the genome as the fundamental unit of the processes of evolutionary biology (Koonin, 2009). This is an interesting example in that it demonstrates the vastly different concepts of the system that emerge when the fundamental unit is changed. The components, process dynamics, dominant scale-level, relationships, and functions of the conceptualized system change concordantly with a change to the fundamental unit; in this debate the central process of evolution sublimates from survival of the fittest species to "error-prone replication of the genome" (Darwin, 1859; Koonin, 2009, p.3).

2.2.2 Land unit

Given the sweeping importance of land to all terrestrial-based life and that many natural phenomena of interest are manifest at or near the surface of the land, many natural phenomena and the systems thereof are described and analyzed as *land units*. Land as defined by the United Nations Convention to Combat Desertification (UNCCD) (1994) means "the terrestrial bio-productive system that comprises soil, vegetation, other biota, and the ecological and hydrological processes that operate within the system" (p.5). The SI measure of an area of land is the hectare, which serves to standardize land area measurement, but is not adequate to identify characteristics of the land other than area, such as terrain or vegetative ground cover, as might be used for the purpose of ecological analysis. The land unit is a fundamental concept and unit of analysis in landscape ecology (Zonneveld, 1989; Sayre et al., 2014) and describes a set of characteristics different than the fundamental unit of the ecosystem, even though the two may exist in the same space. The watershed, or drainage basin, is the fundamental land unit of hydrology (Edwards, et al., 2015); the airshed is the fundamental land unit of airborne particulate deposition (Zirnhelt et al., 2014). Alternatively, the common land unit of the U.S. Department of Agriculture (USDA) (2013) is characterized as having a permanent contiguous boundary, common land cover and land management, a common owner/ producer association, but is applied for accounting convenience. The common land unit does not encompass a functional whole but rather a loose construct that reflects a partial social and economic relationship, not the mechanisms of a whole phenomenon. Consequently the common land unit is more limited in its utility and does not serve as a conceptual or analysis unit, but merely as a unit of accounting.

The delineations of the ecological landscape land unit identified by Zonneveld (1989) can be applied analogously in other land units, including those for energy. First, the land unit is homogeneous in that there are no severe gradients in critical dimensions such that the composing elements occur in regular patterns (Zonneveld, 1989). Ahl and Allen (1996) propose the idea that severe gradients in energy, material, and/or information represent "surfaces" delineating natural units. Second, the land unit defines a natural whole or holism which is recognized as a type by only a few characteristics, and hence the basis of typology or classification (Zonneveld, 1989). A holon is a whole with some degree of autonomy, but at the same time capable of being a part for another whole (Koestler, 1970). The concepts of nesting and self-organization are somewhat inherent also in the concept of the holon (Koestler, 1970; Ahl and Allen, 1996). Finally, the land unit shows gradual change without sudden changes, that is homeostasis and homeorhesis, because of the influence of self-regulation in the system (Zonneveld, 1989).

2.2.3 The impetus for the fundamental land unit of energy

The land unit is a natural integrator and there is exigency and ample conceptual space to conjoin the land unit with energy to derive the fundamental land unit of energy, the energyshed. Water is tightly associated with land in management issues especially those involving sustainability, such as water quality and availability, biodiversity, and soil conservation (UNFAO, 1995). "Land needs energy. Energy needs land" (p.17) suggests that energy production and use, as a primary driver of landscape degradation and climate change, must be associated in the sustainable land planning (UNCCD, 2015). The United Nations (UNCCD, 2015) refers to this management of land tradeoffs between energy and other resources as the land-energy nexus, but it would perhaps be more appropriate to call it the land-energy-water nexus (DeWever, 2010; Smil, 2008, Reisner, 1993). The conditions for securing the land-energy, and water, nexus are: understand the linkages between land, water, and energy supply; small-scale level site-specific solutions are best, especially for biomass energy; plan at the landscape level; promote natural solutions [ecological subsidy]; deliver appropriate levels of connectivity, and consider mini-grids; engage local people, promote ownership, protect rights, and be inclusive; and, achieve land degradation neutrality [or restoration] (UNCCD, 2015). In short, land, water, and energy success metrics are critically linked. The shed construct has been a model of success for integration of land and water health metrics; the energyshed is a logical sequel.

There are additional conceptual and practical benefits to be achieved with the development of the energyshed. The land unit defines measurement in a system, the fundamental unit describes the smallest functional unit from which the process is constructed, and the conceptual unit is an organizing mental structure. The grand energy system lacks a conceptual unit since markets, grid-operations zones, and political boundaries do not capture the essence of the energy phenomenon, nor describe an energy system holon. This is exacerbated at the level of the local government and individual, but is also true of higher levels.

The energyshed has the potential to fill the role of practical unit as well. A practical unit would identify the "energy community" as the foodshed identifies the "eating community" bound by food (Kloppenburg et al., 1996). Within the energyshed unit, the local balance of energy would elucidate the land and water footprint and the impacts of potential trade-offs. As with the watershed, the energyshed could be a management unit, organized to maintain and advocate the coherent function, efficiency, inclusivity, and health of the energyshed and those linked through common energy services. Finally, mated with the capabilities inherent in GIS systems, identification of the fundamental land unit of energy, its function, and organization will increase local capacity for energy governance, planning, and citizen participation (Calvert, 2013; Ganapati, 2010).

2.3 Geospatial relations of energy

The spatial relations of energy as a reference frame is often forgotten or under-considered, and geo-politics and perhaps financials over-considered. This is to neglect a cogent frame for the energy discussion and one that is poignant for RET. Power generation, storage, and end-use occur at a place and in context of the place. That is to say that place permits or constrains the energetically possible, and determines the potential energetic interactions. The impacts and benefits of dissipating power impinge upon place, as does the work produced by the energy.

Information signal describing the transfer and dissipation of power originates in a place and is discerned in a place. The distribution system connects power generation and end-use by the physical path across which the power signal travels. RET generation is typically described by the metric of power intensity in W/m^2, inversely denoting the amount of area required to produce a given power capacity (Smil, 2008) and characterizing a place in terms of its maximum technical potential value for power production and average energy production potential with regards to a specific RET (Lopez et al., 2012).

The following set of axioms describes the relations of energy across the land area of the energyshed.

Physical:

1. *Energyshed components have locations within the energyshed*

This statement might appear self-evident but is not practiced in a globalized energy system.

2. *Energy resources have characteristics dependent on location and geophysical features of the location.*

The energy mapping process incorporates geophysical features (such as terrain, existing infrastructure, vegetation, and associated climate) when determining power capacity potential, energy production potential, temporal behaviors, and feasibility for RET placement.

3. *The energy resource is a continuous field across the energyshed, as are production, end-use, and information*

A continuous field is chosen as the base over a discrete or an object-oriented model since every location has some potential for energy production, end-use, and associated information pertaining to the energy process. Object-oriented models can subsequently be developed from the structures that emerge from the continuous field model.

Process:

4. *Energy transformations (generation and end-use) occur at a location*

As is the case of the physical infrastructure of the energyshed, transforming energy into work and entropy occurs at a location within the energyshed.

5. *Energy transmission through energy carriers occurs across space*

The relationship between an area and nearby areas provides opportunity to "energy average", thus meeting the demand of one area with the capacity of another. The features of the space crossed (distance, difficulty of terrain) affect infrastructure requirements and losses.

Information:

6*. The origination, storage, and receipt of energy-related information occurs at a location; information transmission occurs across space*.

What information is generated, who receives it, and when affect the function, adaptation, and evolution of the system of the energyshed. The information provides feedback for system stability and function.

Flow:

7. *Demand seeks an available supply, and so in this sense, flow occurs from end-use demand outward to generation supply.*

The energyshed is demand-centered instead of the supply-centered model that is predominant in the Organization of Economic Co-operation and Development (OECD). This is appropriate given that greater investment and capital stock resides on the demand side, at end-use, and should more readily shift focus to demand-controlled decisions (Grubler, 2012).

These seven axioms of the spatial relationships of energy reflect the practical human use of energy at a place, in the spatial dimensions; power is the unit that permits analysis of energy along the dimension of time.

2.4 The relations of power and energy in the energyshed

Power is often defined as the rate of performing work, although this is a limiting definition (Halliday and Resnick, 1981; Benenson et al., 2006). Power is the time rate of change of producing or expending energy and represents a time rate of change of energy transfer, or conversely energy is the integration of power over a time (Roadstrum and Wolaver, 1987). As power is expended, both exergy and entropy in a system change. The capacity of electrical equipment is rated in power in the unit of watts, which is one joule of energy per second.

Power is the building block of energy and the energyshed, and energy is the integration of all instances of power in a time period. The relations of power are basal to the construct of the energyshed and will form many of the emergent behaviors and properties of the energyshed. Sometimes applying the unit of energy is useful for planning and designing; ultimately though, to understand all of the implications of that energy, units of power must be applied to understand system behavior through time. Emerging patterns from power balance produce energyshed behaviors over time. For the electrical grid, which is a power system, relationships are only intact when power is flowing through system. All generation, end-use, storage, and distribution connected at that moment dictate instantaneous system properties and behavior. That is the momentary system configuration and state. Other potential but disconnected generators and loads are not acting as part of the system in that moment. Power sharing over the distribution system relates them. As component element behavior varies or component elements are added or removed, the system will have slightly different configuration and thus characteristics at that time. The system will oscillate between various limit cycles, or extent extrema, produced by the extreme-most configurations of power. Power captures the intermittency inherent in renewables resources, whereas energy, as a time average, is the higher-temporal-level pattern formed from power, but energy does not capture all of the important momentary relationships that produce limiting conditions in the energyshed. Some limiting conditions that will occur in the context of power include minimum and maximum boundary and enclosed area of the energyshed and required storage capacity to bring the minimum and maximum boundary of the energyshed closer together to reduce extent oscillations. Power will also define the dynamics of the system to a great extent. In one sense, the energyshed can be considered as a series of powersheds through time.

Energy as a metric is also important in the energyshed. Several useful data sets are aggregated in terms of changes in energy as calculated over a time period, such as daily or monthly, but often annually. Disaggregation of the data into time-series may be required in some cases but the aggregate will also provide useful averaged information for the energyshed. Many energyshed properties will be best described with energy as the metric such as seasonal or annual energy balance, cumulative impacts, and energy infrastructure changes. Energy is useful in describing stored energy including solid, liquid, gaseous fuels, and energy stored in batteries and thermal or mechanical energy storage systems.

In the energyshed concept, clear distinction between energy and power is at times required and so I will carefully apply the two terms. Energy will be applied broadly in general discussion to describe the rationale behind the energyshed and will remain consistent in its meaning of a net change over time in system capacity, state, or configuration to perform work. Power will be used to evoke the idea of instantaneous transfer of energy and of the energyshed system in its instantaneous state.

2.5 Defining the energyshed

Upon review of other frameworks utilizing the shed concept, it is evident that the energyshed system could be defined from multiple perspectives, such as coherence of regional distribution operations (Hughes, 2009), political boundary (Burgess, et al., 2012; Khanna, Jenkins, and Niemeier, 2010), or the physical location which provides the supply (Kloppenburg, Hendrickson, and Stevenson, 1996; Peters, Bills, Wilkins, and Fick, 2009), or deposition (Zirnhelt et al., 2014) and yet, as a shed, it must always associate to a land area. With governance in mind, it is tempting to pursue a definition that utilizes a political boundary since the community residing within would have pre-existing organizational structures and jurisdiction with which to enact change and manage the system. However, with energy, as in the case of the watershed, the foodshed and the airshed, the extents of the physical processes that define the shed as a coherent system rarely align with political boundaries (Conca, 2006; Reisner, 1993; Kloppenberg et al., 1996; Okrainetz, 2011; Gunderson, Holling, and Light, 1995). The energyshed definition is conceived to identify the coherent physical phenomenon of renewable energy and its relationship to the land area in which it sits. This physical phenomenon of energy is not independent of time and so power was chosen as the most basic unit of the energyshed, with understanding that time integration of power produces energy.

2.5.1 Energyshed definition

An energyshed is simply defined as that area in which all power consumed within it is supplied within it.

An energyshed boundary encircles an area in which power, the instantaneous expression of energy, is balanced such that demand is met without surplus in a perfectly-connected network (Figure 1). This shed boundary is affected by the quality of the renewable resource, generation capacity, presence of storage, end-use demand and efficiency thereof. Energysheds are conceivably nested within larger energysheds.

2.5.2 Energyshed purpose

The purpose of an energyshed is to provide the functions and structure to harvest and dissipate energy to support life, activity, and productivity throughout the energyshed without polluting the environment above its capacity to assimilate those pollutants.

2.5.3 Basic functions within the energyshed

The basic functions performed within an energyshed are resourcing, generating, distributing, storing, and dissipating energy by the community of the energyshed.

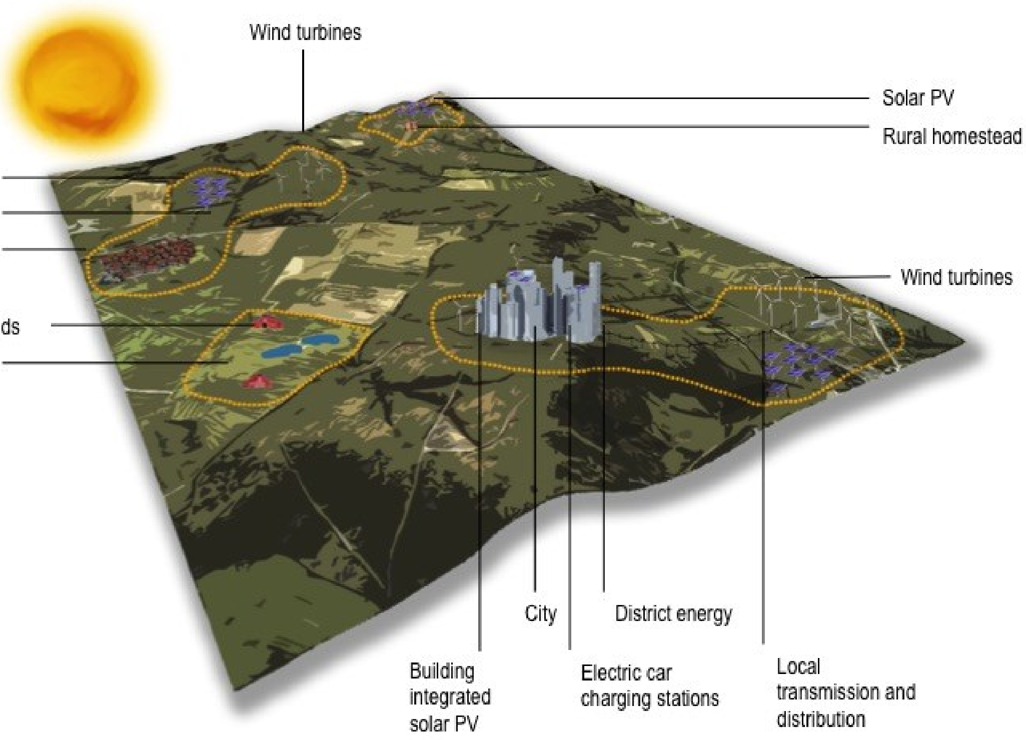

Figure 1. Energyshed

CHAPTER 3. SYSTEM COMPONENTS

Within the bounds of the energyshed are the components and relationships that comprise the energyshed system. A general definition of a system is "an open set of complementary, interacting parts with properties, capabilities and behaviors, emerging both from the parts and from their interactions" (Stasinopoulus et al., 2009). These interacting parts are coordinated to accomplish a goal and there is a boundary across which change can be measured (Churchman, 1979; Meadows, 2008; Ahl and Allen, 1996). Energy systems are complex; the concept of energy permeates all academic disciplines (Smil, 2008) and may be viewed from multiple lenses from technical (Willis and Scott, 2000; Duffie and Beckman, 2006) to geopolitical, as through the lens of energy security (Sovacool, 2011), to energy process chains (Hughes, 2012). A power-engineering lens brings consideration of the system as generation-plant-centric; a plant electrical power system is comprised of the plant distribution system of connection network, with switching, protection, and metering equipment connected to loads (Roadstrum and Wolaver, 1987). Most often energy systems are categorized through type of energy carrier such as electricity or natural gas, and services provided, for instance lighting or space heating (BP, 2014). Tester et al. (2005, p9-10) defined an energy system as the bounds within which the change in energy content can be measured. Willis and Scott (2000) hint at definition through function, stating that an energy system provides the following minimum functionality: production, distribution, and end-use of energy across the area serviced by the system. There is not a single accepted definition of what comprises an energy system, let alone one of municipal size and complexity.

Eight energyshed components were defined to further detail the energyshed system. They span the overall processes within the energyshed from energy resource entering the shed to final end-use conversion of the power with waste heat exiting the shed on completion of the cycle. The components are resource, generation, distribution, energy carrier, storage, end-use, waste heat, and information (Figure 2). With these eight components, the physical process of the energy system can be modeled and the spatial relationships among them can be explored and analyzed to identify the properties of the energyshed.

An electricity-based example is as follows. The solar resource enters the shed and is captured by the RET, an example being the photovoltaic panel. The photovoltaic panel converts a portion of the available resource to electrical power. A solar thermal panel would potentially compete for the solar resource and would commence a new power chain, in this case thermal. Both the electrical chain and the thermal chain may require some transmission and distribution infrastructure and may also have storage capacity integrated into the system. Both power chains undergo conversion according to the 2nd law of thermodynamics to useful work and into a lower quality power, ultimately becoming waste heat. If the waste heat is of a quality sufficient to do more work to include heating service, then it may start another cycle within the shed, be distributed, provide benefit to an end-user, and then ultimately "exit" the energyshed once it is no longer of a usable quality. Information is generated during each stage of the process for control signals, feedback, adaptation, and ultimately evolution of the system.

3.1 Resource

For the energyshed framework, the resource is the energy source entering the shed area. Daly (1990a) proposes an operational principle for identifying a renewable resource as, the "sustainable rate of use can be no greater than the rate of generation." The five renewable energy resources that may be present in a given energyshed are: solar energy, wind energy, geothermal energy, bioenergy, and energy from water (NREL, 2015).

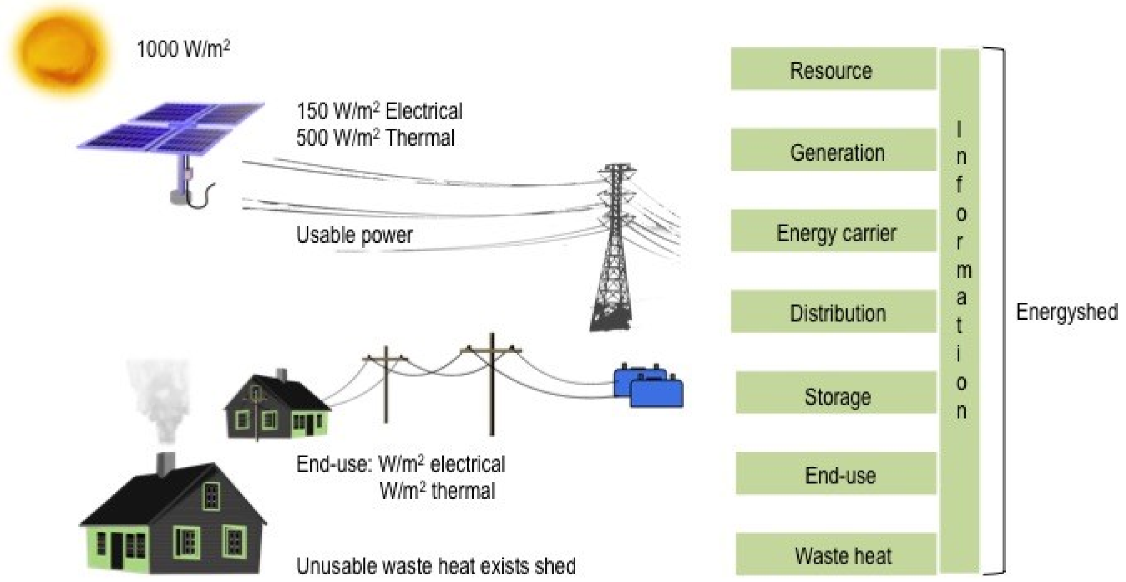

Figure 2. Energyshed components

Characterizing the renewable energy resource present in an area is frequently accomplished through remote sensing, mapping, and GIS. National and regional resource characterizations are widely available in North America and Europe (for example Wilcox, 2012; GoeNova, 2007). Analyses of the technical potentials for renewable resources are also becoming readily available (Lopez et al., 2012). National- and regional-level resource maps are useful as an initial coarse evaluation of the renewable resources within a region and serve as a starting point for local analysis, although in many cases do not provide the resolution necessary to integrate with municipal-level planning detail.

Recent advances in computing performance and high-resolution remote sensing technologies such as light detection and ranging (LiDAR) are promoting high-resolution energy mapping at the municipal level. Often high-resolution mapping serves many purposes within a municipal planning process from sea-level-rise studies to viewshed analysis. These high-resolution data sets can be commissioned or re-purposed for solar shading studies in urban areas, high-resolution wind analysis, passive solar and daylighting analysis for building design, and RET siting and zoning analysis, serving as the foundation for energy potential mapping at the municipal level. Some examples for local energy potential mapping include the advanced method used in the Cambridge Solar Map or integrated heat mapping for the Netherlands (Jakubiec and Reinhart, 2013; City of Cambridge Massachusetts and Mapdwell, 2013; van den Dobbelsteen, Broersma, and Fremouw, 2013). Integrated resource multi-criteria decision aids provide a holistic method for analyzing locally available energy resources, engaging the community, providing a baseline for planners, and identifying potential siting locations for each RET considered. An analysis of this sort was completed for North Vancouver (Schroth, Pond, Tooke, Flanders, and Sheppard, 2013).

3.2 Generation

RETs harvest a fraction of the power flux from the renewable resources and produce usable power for direct use in the energy network. Lopez et al. (2012) compiled total estimated technical potential generation and capacity in the United States for renewable technologies. The table below illustrates the substantial capacity available to meet the demand of a high-per-capita-energy-using nation, in this case the analysis for the United States. Technical potential is not limiting across the United States as a whole (Lopez et al., 2012), although renewable generation requires substantially more land area than conventional fossil fuels so generation will require significant land-use restructuring (Smil, 2003).

3.2.1 Solar energy

Solar RETs can be categorized into two broad types: photovoltaic and solar-thermal. Photovoltaic (PV) systems convert solar radiation directly to electricity using the properties of semi-conductor junctions (Messenger and Ventre, 2004; Lasnier and

Ang, 1990). Solar thermal can be active, using collectors, or passive, which refers to using the building structure to capture heat, encourage convective air flow or provide day-lighting (Tester et al., 2005). Single collectors are suitable for domestic hot water and space heating services, while concentration of solar energy from mirrored systems is necessary to produce heat of high enough quality to drive turbines to produce electricity (Duffie and Beckman, 2006). With the exception of electricity generation by solar concentrators, PV and thermal systems are finely scalable, modular, relatively inexpensive and widely suitable for integration within the typical municipal fabric. Solar PV and flat-plate-collector solar thermal systems have an averaged generation power density (power/area) of roughly 20-60 W/m^2 that matches well with end-use-power density of residential and low-intensity commercial activities of 20 to 100 W/m^2, as well as the average power density across a city (Smil, 2003). Instantaneous power capacity is greater at roughly 170 W/m^2 and 600 W/m^2, respectively. From Table1, solar PV has the greatest potential, albeit in diurnal cycles, across the United States and likely as well across southern Canada. Solar thermal, active or passive, was not considered in the technical potential in Table 1.

3.2.2 Wind energy

The wind resource, which is ultimately driven by solar-forced convection, is harvested with wind turbines directly producing electricity. Wind turbines scale from a rooftop miniature on the kilowatt scale to mammoth, offshore turbines of five or more megawatts. Friction and obstructions near the land surface significantly reduce the resource below 30 metres (Johannson et al., 1993). 50 metres to more than a 100 metres is the typical hub-height of most commercial-scale turbines. Mutual interference and turbulence requires adequate spacing to separate the turbines, thus making wind turbines a diluted source of energy generation (Tester et al., 2005; USDOE, 2010). As a comparison, wind turbines have a generation power density one order of magnitude less than solar (Tester et al., 2005). Wind turbines have more restrictive siting requirements than solar. Aesthetics and noise are cited as primary causes of social resistance to wind turbines, which are then important considerations for siting (USDOE, 2010). Intermittency is a primary technical concern for grid stability especially given larger machines and large wind fields (Tester et al., 2005).

Table 1. United States 2014 estimated technical potential generation, percentage of primary energy consumption, power density, and installed RET capacity

Total est. technical potential generation (TWh) [1]	Tech potential as a % of total primary energy use (10,114 TWh) [2*]	Generation power density with existing technologies (W/m^2) [3]	Total electrical generation by RET (554 TWh) [5] [5.5% of total pri. energy use]
Photovoltaics (399,700)	3952%	20 – 60	32.6 [0.32%]
Wind power (49,700)	491%	5 - 20	182 [1.8%]
Biopower (500)	4.9%	1	64.3 [0.64%]
Geothermal (31,600)	312%	0.085 (hydrothermal) 1000 (enhanced)	16.6 [0.16%]
Water: Hydropower (300)	3%	10 – 50 (tidal and river flow) 1 (dam and reservoir)	259 [2.6%]
Water: Ocean power (worldwide 500 – 1000) [4]	No data	1 (ocean heat) 10-20 (tidal)	No data

(adapted from Lopez et al., 2012 Table 12[1]; BP, 2015[2]; Smil, 2003 Figure 5.2[3]; Johansson et al., 1993[4]; USDOE, 2015b[5])

* This is a very conservative comparison since significant losses are inherent in conversion of primary energy to secondary energy and then again at end-use in heat engines. In reality several times less renewable energy will be required than current primary energy use.

The best wind resources tend to be close to a coast and not inland. In many regions this matches with population centers, as three quarters of the world's large cities and over half of the world's population live within 60 kilometres of a coast (UNEP, 2015). This provides opportunity for siting wind fields, on- and off-shore, in relative proximity to population centers, integrated within the energyshed. Wind RETs are also suitable for off-shore and non-arable land siting. The turbine footprint is small compared to the elevated area it sweeps meaning that its direct land-use footprint is its base and any logistics area required (USDOE, 2010). Wind is thus suitable for co-siting with farming and other RET generation. From Table 1, wind power, on- and off-shore, has a substantial United States technical potential.

3.2.3 Geothermal energy

North America is endowed with a substantial geothermal resource as shown in Table 1, although it is not well distributed, primarily concentrated in the western portion of the continent (Lopez et al., 2012). Geothermal generation is relegated to those areas with geothermal energy near enough to the surface (<10 km) and of high enough quality to warrant development. Hydrothermal is a lower quality energy transferred via hot water, usually at depths of 2-4 km (Tester et al., 2005). Low-quality geothermal power density averages 0.085 W/m^2 (Smil, 2003) available everywhere, all the time. In a broader interpretation, ground-sourced heat pumps may also fall into this category and, with a coefficient of performance of 4 as typical, gather 4 units of heat (or cooling) for every 1 unit consumed. Hydrothermal is suitable for space heating and domestic-hot-water production, although higher quality hydrothermal sites are suitable for electricity generation.

Other methods of geothermal energy include heat extraction directly from magma and extraction of energy from geo-pressured brines (Tester et al., 2005). Enhanced geothermal, also known as hot dry rock, is the greatest potential geothermal source (Tester et al., 2005; Lopez et al., 2012). Enhanced geothermal systems circulate water into fissures in dry hot rock at depths of up to 10 km to extract heat, at temperatures often suitable for electricity generation (Tester et al., 2005). Enhanced geothermal is more widely distributed across the North American continent than is hydrothermal (Lopez et al., 2012). Along with depth and quality, rock characteristics and water chemistry at the bore site can greatly affect geothermal viability (Tester et al., 2005). Since enhanced geothermal is deep underground, surface land-use conflict is minimal, but rights to geothermal resources and potential interactions between neighboring geothermal systems may require planning and deconfliction. Geothermal power suffers from the fact that there is no direct-heat geothermal industry or infrastructure as there is for electrical power (Tester et al., 2005).

3.2.4 Bioenergy

Bioenergy describes a diverse set of fuels derived from biomass, which is defined as "all living plant matter as well as organic wastes derived from plants, humans, marine life, and animals" (Tester et al., 2005, p. 420). Prior to coal and as late as the second half of the 19th century, biomass was the primary source of energy. In many developing countries, biomass remains a primary energy source for domestic uses such as cooking and heating (Tester et al., 2005; Rutter and Keirstead, 2012). Bioenergy from biomass accounts for nearly 3% of United States energy production (Tester et al., 2005) and 10% of world energy production (Löschel et al., 2010). Biomass can be produced sustainably, of which less than half currently is (Löschel et al., 2010), or unsustainably, meaning that it is not technically a renewable resource (Daly, 1990a).

The advantages of biomass include geographic distribution, domestic availability, carbon-neutrality or potentially carbon negativity, fine scalability in production processing and energy generation, offset to municipal waste, less sulfur and less airborne particulate than coal (Tester et al., 2005). Biomass also has widespread uses as food, animal feed, and feedstock for industrial production. Biomass can be converted into a wide range of useful forms of energy including heat, steam, liquid fuels, electricity, and fuel gases to include methane and syngas, which can also be used for fertilizer production (Tester et al., 2005). Biomass is a flexible commodity and thus can become supply-constrained.

Bioenergy has several disadvantages including low heat content and high moisture content often requiring substantial energy input for drying and other processing. Bioenergy has severe constraints due to the potential environmental impacts and resource conflicts with fresh water and arable land, potentially leading to food-versus-fuel and water-versus-fuel conflicts (Löschel et al., 2010). Over-production can result in local loss of biodiversity, loss of topsoil, and ecological system collapse leading to desertification (Tester et al., 2005). Bioenergy processes also require substantial energy and fertilizer inputs for cultivation and energy for processing, in some cases requiring more energy than usable energy produced, i.e. energy return on energy invested is less than one (Löschel et al., 2010). Use of waste materials from agricultural, industrial, and municipal processes is often beneficial since cultivation and some processing costs are offset, but supply of waste feedstock is ultimately limited (Johannson et al., 1993). Partly because of its low power density on the order of 1 W/m^2 (Smil, 2003), bioenergy has a limited technical potential generation (Lopez et al., 2012). Advances in marine bioenergy, both land-based and ocean-based production, show promise to expand the technical potential generation but technologies and processes are not mainstream as yet (Sheehan, Dunahay, Benemann, and Roessler, 1998). Despite the potential pitfalls, bioenergy is and will remain an important component of the renewable energy mix of many locales.

3.2.5 Energy from water

There are many methods of extracting energy from water resources, grouped into hydropower and ocean power. Hydropower refers to several technologies that include impoundment of stored water behind a dam, or extracting kinetic energy from flowing water in the "run-of-the-river." Hydropower is the largest source of renewable energy generation producing 20% of all electricity generation world wide (BP, 2015; Tester et al., 2005). Hydropower has many advantages such as low cost, low maintenance, long lifetime of capital infrastructure, matured knowledge base, scalability, no combustion of fossil-fuels, rapid dispatching, potentially large capacities, and integrated water-supply uses for agriculture, power, recreation, drinking water supply, and flood control (Tester et al., 2005). Hydropower, particularly with impoundment dams, can have significant environmental impacts, depending on location and project design, to include loss of land from flooding, riparian and aquatic ecosystem destruction, fish migration interference, and carbon emissions from cement used in construction (Johansson et al., 1993; Tester et al., 2005). Environmental and social impacts have slowed new dam construction in the United States and encouraged removal of existing and aging dams. In the United States, hydropower has modest technical potential generation as compared to solar, wind or geothermal (Lopez et al., 2012). Use of hydropower varies across regions and in South America it accounts for 75% of electrical generation across the continent (Tester et al., 2005). Siting for hydropower systems is restricted to the specific locations of the resource, which although are reasonably well distributed may not be available locally or regionally (Lopez et al., 2012). Power density varies by an order of magnitude across technologies, from as little as 1 W/m^2 for impoundment dams with large reservoirs to 10 to 50 W/m^2 for run-of-the-river systems (Smil, 2003).

The ocean houses a vast reservoir of energy, much of which is dilute and low quality as in thermal and salinity gradients. On the other hand, kinetic energy in the form of tides, currents, and waves can be very powerful and concentrated. Thermal and salinity processes use the gradient in temperature and salt contents in vertically stratified water columns to drive turbines or for direct electron production as in a battery. Power density is low, on the order of 1 W/m^2 and salinity processes are not currently economically viable (Smil, 2003; Tester et al., 2005). Wave and tidal power use a variety of devices, from turbines to vertical floats, to generate electricity. A tidal range of at least 3 m is required for viable tidal power processes so suitable sites are limited (Johansson et al., 1993). Yet for regions with suitable sites, such as the Bay of Fundy with an estimated potential of 60,000 MW, harnessing some of that capacity is attractive (Energy Nova Scotia, 2015; Energy

Nova Scotia, 2012). Wave power is most suitable between latitudes 40^0 and 60^0 driven by persistent trade winds and most suitable on the west coast of the United States and Europe and the coasts of Japan and New Zealand (Johansson et al., 1993). Ocean technologies are reasonable scalable. Power densities for tidal are 10 to 20 W/m^2 and are similar to run-of-the-river hydro for wave and current at 10 to 50 W/m^2 (Smil, 2003; Johansson et al., 1993). Both wave- and tidal-power systems incur risk of damage or destruction during storms, thus requiring robust infrastructure and detailed design studies (Tester et al., 2005; CBC News, 2014). Ocean technologies are immature and off-shore technologies incur additional costs and risks and so hydropower will likely lead development over ocean technologies for the foreseeable future (Tester et al., 2005).

3.3 Distribution

The purpose of a distribution system is to connect a supply to a demand. Petroleum products, natural gas, biomass, and electrical power have robust distribution systems. These systems also have a long-distance transmission component of the broader distribution system. Storage is a related function and is often grouped with transmission and distribution (USDOE, 2015a). The systems are designed differently, exhibiting radial, networked, and/or fractal topologies, which in turn affect cost, reliability, efficiency, and operations of the systems (Laurienti, Joyce, Telesford, Burdette, and Hayasaka, 2011; Willis and Scott, 2000; Willis, 2004).

The long-term trend of electrification of the energy system (Smil, 2008), broad reliance on the electrical power grid, and models predicting that the trend will continue (Edmonds, Wilson, Wise, and Weyant, 2006) suggest that it is worthwhile to bring the focus of this discussion of energy distribution to the electrical power grid. Electrical transmission and distribution systems are highly interconnected, producing some of the largest and most complex engineered systems in the world (Willis, 2004; USDOE, 2002). The electricity grid as originally conceived and built was an awe-inspiring system, designed for excellence and not left to mediocrity (Roadstrum and Wolaver, 1987). Yet, increased loading, lagging investment, market liberalization, significant energy losses in the system, and penetration of RETs onto the grid have produced further stress on the aging and now somewhat brittle system, raising the question as to the need to redesign the infrastructure and organization of the electrical power grid (USDOE, 2002; Tester et al., 2005; Johansson et al., 1993; Volk, 2013; Willis, 2004). Additionally many of the limitations of thermoelectric plants, for example improved thermal efficiency with increased size, are mitigated in new generation systems such as PV, and alternatively, new issues such as intermittency arise.

Specific distribution of cost, impacts, and benefits is an important social and political question when considering major upgrades to the electrical power grid. These costly grid infrastructure decisions are often cost-rationalized over decades (Tester et al, 2005),and so infrastructure design decisions will shape the electrical power grid for the foreseeable future and could result in stranded assets if not able to evolve with generation and demand-side technology changes. Grid design goals include: safety, reliability, maintainability, simplicity, good voltage regulation, minimizing cost of installation and operation, and flexibility particularly with respect to future changes and expansion (Roadstrum and Wolaver, 1987).

The primary mission of the electrical transmission and distribution system "is to deliver power to electrical consumers at their place of consumption and in ready-to-use form" (Willis, 2004, p2). The functions of the transmission and distribution system are to: 1) cover the service territory; 2) have sufficient capacity to meet peak demand; 3) be reliable; and 4) provide stable voltage and frequency (Willis and Scott, 2000, p12). Key characteristics of the electrical transmission and distribution system vary with level in the system and also demark the boundary between transmission and distribution (Table 2) (Willis and Scott, 2004). Trends shown in Table 2 are referenced from upper level to lower, from the power generating station to the end-user.

Table 2. Transmission and distribution system characteristics across levels

Transmission and distribution system characteristics	Power generation station	End-use / customer
Power feed	push	pull
Voltage	high	low
Components	fewer	many
Net capacity	decreases	increases
Reliability	increases	decreases
Configuration	networked, interconnected	radial, single connection

(adapted from Willis, 2004; Tester et al., 2005; Willis and Scott, 2000)

Willis (2004) proposes six principles that have greatly affected the design and operations of electrical power distribution systems (Figure 3). Many electrical power distribution systems are organized for centralized generation to support large generating stations, which are often situated far from population centers of end-users, partly due to pollution and safety concerns (Willis and Scott, 2000). On the continuum from centralized to decentralized electrical power grids, dispersed generation refers to the use of small generating units co-located with the end-user and is a subset of distributed generation (Willis and Scott, 2000). Distributed generation is used to describe the use of all generating systems, through the full range of sizes and types, throughout the distribution system, including both local and centralized siting (Willis and Scott, 2000). Evolving the grid through integration of distributed RET provides opportunity to benefit from full use of existing infrastructure, offset some of the needed transmission infrastructure upgrades, and reduce transmission and distribution losses (Geidl, 2007).

Figure 3. Six principles influencing electrical power distribution systems

	Six Principles Influencing Electrical Distribution Systems
1.	Moving power at high voltage produces much less transmission loss
2.	Higher voltage equipment has greater power transfer capacity and thus costs substantially more than similar low-voltage equipment
3.	Utilization voltage (120 / 240 V) can only move electricity a few hundred metres without incurring prohibitive losses and equipment costs
4.	Changing voltage incurs losses
5.	Thermodynamic efficiencies favor large generation systems*
6.	Power must be delivered in small quantities at utilization voltage (120/240V) and the average customer uses only 0.01% to 0.001% of the power produced by a large generator

* This applies to heat engines. It also applies to wind turbines, but for reasons of blade efficiency. It does not apply to photovoltaic systems.
(Adapted from Willis, 2004, p6)

3.4 Energy carriers

Primary energy is an energy source as it is first encountered and has not been subjected to a conversion or transformation process (OECD, 2001; EIA, n.d.). These sources are from fuel extraction or primary electricity generation (from hydropower, geothermal, nuclear, and solar generation) (Smil, 2008). Primary energy sources are: oil, natural gas, coal, nuclear, hydroelectric, and renewables (wind, geothermal, solar, biomass, and waste) (BP, 2015). Secondary energy is produced through transformation of primary energy to a form suitable as an energy carrier. Energy carriers transfer energy through the energy chain from primary energy sources to end-users and include electricity, heat, and solid, liquid, and gaseous fuels (UNIPCC, 2007). Hydrogen is a clean, energy-dense, and efficiently storable energy carrier of potential future significance (Hoffman, 2001; Tester et al, 2005; UNIPCC, 2007). Hydrogen can be sourced from multiple technologies and, although technically feasible, is not in widespread use to date (Hoffman, 2001; UNIPCC, 2007). Important characteristics for energy include high energy density, storage efficacy, versatility, transportability, and safety. Although energy carriers do not have a spatial dimension, except maybe when stored, energy carriers experience losses, or costs of transport, over transmission distance. Two notable global trends of energy carriers are: a trend toward higher quality fuels, from coal to petroleum and now toward gases; and second toward converting a higher proportion of fuels to electricity, or electrification (UNIPCC, 2007; Smil, 2008).

The ubiquity and versatility of electricity and liquid and gaseous fuels are clear; the importance of heat as an energy carrier is not as obvious and deserves some attention. Unlike electricity, natural gas, and refined petroleum products, heat does not have an established heat-utility industry behind it. Most homeowners do not currently have the option to buy heat piped to their house. Heat stores efficiently inside thermal mass but can only be efficiently transmitted 1 to 2 km (Tester et al., 2005; UNIPCC, 2007). Cogeneration systems can well exceed energy efficiency of 60% under fluid operating conditions, essentially doubling the energy efficiency of single-cycle-electro-thermal generation systems (Turconi, Boldrin, and Astrup, 2013). In cogeneration, waste heat from electro-thermal generation is captured and used for co-located or nearby lower quality end-uses, such as space heating, industrial process heat, or domestic hot water heating. Solar thermal systems, which are reliable and simple (NREL, 2015), can supplement and eventually supplant waste heat from fossil-based electro-thermal generation to supply nearby low-quality heat demand.

3.5 Storage

The term energy-storage system refers to a wide range of technologies that accumulate energy for discharge at a later time (USDOE, 2013). In general these systems consist of the storage technology, converters if required, and control system (Sauer, 2008). Examples of energy storage systems include batteries, pumped hydraulics, compressed air energy storage (CAES), thermal storage, geothermal storage, energy storage in fuels, and kinetic energy in flywheels. The National Renewable Energy Laboratory (NREL) (2012) classifies storage associated with the electrical power grid into three categories by discharge time: power regulation (seconds to minutes), bridging power (minutes to < 1hour), and energy management (hours). Recent employment of seasonal-duration storage such as in geothermal cold storage systems (for example HRM, 2011), and policy requiring 90-day petroleum supply for countries belonging to the Organization of Economic Development and Cooperation (IEA, 2012), indicate that a fourth classification, seasonal spanning (months), is appropriate when looking at energy storage beyond that directly tied to the electricity grid.

Integrating storage into an energy system addresses four needs: 1) dispatchability for response to demand fluctuations; 2) interruptibility for response to intermittency in generation; 3) efficiency of the energy cycle through waste energy recovery; and, 4) regulatory-driven requirements (Tester, et al., 2005). Storage provides a buffer, is important for energy system stability, and can be used to improve energy chain efficiency from generation to end-use (Duffie and Beckman, 2006; Willis and Scott, 2000; Tester et al., 2005). As a mediator between variable loads and variable demand, which is of particular importance for intermittent renewables, storage temporally decouples supply and demand by moving energy through time, or time-shifting (Akhil et al., 2013;Tester et al., 2005). Storage is currently employed with both conventional and renewable generation sources (Akhil et al., 2013). A flexible asset, storage can provide a wide range of services and functions for an energy system and may provide "stacked" functions, servicing several needs simultaneously (Table 3) (Akhil et al., 2013). Capacity, duration of discharge, quality of output, and location within the grid play an important role as to where and how storage systems may function within the overall system (Akhil et al. (2013).

Integrating storage into the electricity grid requires balancing overall grid or energy system performance with oft-times competing storage system performance characteristics (Willis and Scott, 2000). Important storage performance characteristics are: energy density, power density, electrical efficiency, control system, service lifetime and cycles, physical dimensions, and cost (Willis and Scott, 2000). Sauer (2008) contributes a few more to include response times, temperature range, safety, maintenance, recycling, and ability to estimate functional status such as charge level. An example of a tradeoff might be low energy density that requires a large physical dimension, which may not be practical for some applications such as air travel or siting in a residential area. Pumped-hydro storage and CAES systems are currently the dominant forms of energy storage in use because of high capacity and large storage but the availability of geologically suitable sites is limited and dictates asset location (NREL, 2012). Batteries and other methods struggle with energy and power densities, and with cost, but are ideal for distributed employment because of their fine scalability and even mobility (Smil, 2003; Akhil, 2013; Willis and Scott, 2000). New battery technologies are pushing cost, size, control and capacity limitations and as such the battery technology is likely ready for wide-spread and distributed penetration into the grid alongside intermittent RETs, in electric vehicles, and in residential and commercial applications.

Along with technological issues, which are being resolved, market issues are the primary hindrance to more ubiquitous employment of storage onto the grid. De-regulated energy markets de-value energy storage for individual actors (Kleinberg, 2014; Denholm, 2013). Storage produces greater benefit to the electricity grid as a whole [regionally] than it does to individual actors in a de-regulated grid (Denholm, 2013; AECOM, 2015; Kleinberg, 2014). This has proven to be a challenge to augmenting the grid with storage capacity. Also, storage can be viewed as a net energy consumer, as a load, which incurs operating costs (NREL, 2012). Denholm (2013) finds that the value of storage as a reserve (spinning, non-spinning, or supplemental) is more beneficial to the system than if employed for load leveling. Offsetting needed generating capacity upgrade may prove to be a tipping point for utilities at the edge of generating capacity to invest in storage. Full-cost accounting of the benefits and costs of storage is likely required to coax the market into the lead over regulation in adding needed storage capacity.

Table 3. Storage services and typical system requirements

Storage services	Functions	Storage capacity	Discharge duration
Bulk energy services	1) time-shift or arbitrage;	1 - 500 MW	<1 hr
	2) supply capacity	1 - 500 MW	2 – 6 hrs
Ancillary services	1) regulation;	10 - 40 MW	0.25 – 1 hr
	2) (non-) spinning and supplemental reserves;	10 – 100 MW	0.25 – 1 hr
	3) voltage/reactance support;	1 – 10 MVAR	NA
	4) black start;	5 – 50 MW	0.25 – 1 hr
	5) load-following;	1 – 100 MW	0.25 – 1 hr
	6) ramping support for RETs;	1 – 100 MW	0.25 – 1 hr
	7) frequency response		
Transmission infrastructure services	1) upgrade deferral;	10 – 100 MW	2 – 8 hrs
	2) congestion relief;	1 – 100 MW	1 – 4 hrs
	3) stability damping;	10 – 100 MW	5 s – 2 hrs
	4) sub-synchronous resonance damping	10 – 100 MW	5 s – 2 hrs
Distribution infrastructure services	1) upgrade deferral;	0.5 – 10 MW	1 – 4 hrs
	2) voltage support	0.5 – 10 MW	1 – 4 hrs
Customer energy management services	1) power quality;	0.1 – 10 MW	10 s – 0.25 hr
	2) reliability;	various	various
	3) retail energy time-shift;	0.001 – 1 MW	1 – 6 hrs
	4) demand charge mgmt.	0.5 – 10 MW	1 – 4 hrs

(Adapted from Akhil et al., 2013)

3.6 End-use

The final step in an energy chain is end-use during which energy is converted to useful work, waste-heat, and the associated entropy increase that occurs with both. The preponderance of energy end-use, approximately 70%, occurs in the context of human settlement and feeds the urban metabolism (Butera, 2008; Hammer, 2008). The majority of capital expenditure associated with energy infrastructure occurs on the end-use, or demand-side, of the system in OECD nations (Grubler, 2012). Energy consuming appliances complete the trends in modern energy systems from generation through transmission and distribution to end-use of: increasing capacity, increasing capital investment, and increasing land-use requirements (Willis and Scott, 2000; Smil, 2008; Grubler, 2012). In the initial stages of transition, performance characteristics of a technology are more dominant than price for the early adopters (Grubler, 2012). The comparative advantage of multiple performance dimensions affects end-use more so than it does for supply technologies (Grubler, 2012). Supply and demand technologies co-evolve and so end-users have a significant role in leading and defining energy transition alongside organizational and institutional change (Grubler, 2012). These characteristics of historic energy transition indicate compelling opportunity to expedite decentralized transition to RETs from the bottom-up with drive from the lower levels of spatial and organizational scale of individual to cities and municipalities (Grubler, 2012).

Along with vulnerability posed by climate change, cities and municipalities are beginning to realize the important and powerful role that they have in leading change in the energy system. Cities and municipalities are the full-service level of government most local to the energy end-users, their constituents. These local governments are also large consumers of energy, which is required to provide municipal energy–intensive services such as freshwater filtering and distribution, wastewater remediation, and road maintenance. Many municipalities have integrated energy planning into their governing process (St Denis and Parker, 2009). Primary strategies for Canadian municipalities, which seem to be common in developed nations, include efficiency measures and conservation, both targeting energy end-users (St. Denis and Parker, 2009). Canadian municipalities have been much slower to address the supply-side of the equation by advancing measures to increase RET capacity (St. Denis and Parker, 2009). Brown and Sovacool (2011) consider improved energy efficiency to also include energy conservation and energy productivity, to provide the greatest potential near-term greenhouse gas mitigation potential.

Cities and municipalities have many roles that can directly or indirectly alter the nature of the energy system in the locale. Local government provides the following roles affecting the local energy system: direct service delivery, regulator including land-use zoning and building codes, buyer and purchasing power, land-owner, developer, building operator, advocator, educator, public health protection and environmental protection (Hammer, 2009). Local governments are often constrained by state and national policy (Hammer, 2008), yet they are not as tied to geo-politics and legacy generation infrastructure as higher levels of government and so offer potential fluidity for energy transition (Scheer, 2008).

3.7 Waste Heat and Entropy

Waste heat and entropy production are the result of thermodynamic processes used in an energy system as governed by the second law of thermodynamics (Mortimer, 1987). The maximum efficiency of heat engines is described by the Carnot Cycle, which states that heat must be rejected to produce work (Johnston, Brockett, Bock, and Keating, 1978). Typical efficiencies for single-cycle thermal-electric generation machines range between 28% for older combustion boilers to 40% for a modern gas turbine operating at high temperatures (Tester et al., 2005). The remainder of the energy from combustion of the fuel exits the system as waste heat, which is no longer of quality suitable for effectively generating electrical power (Johnston et al., 1978). A portion of that waste heat can be captured in combined cycles and redistributed as thermal energy for lower quality uses such as cooking, space heating, and industrial process heat (Tester et al., 2005).

In an energy cascade from resource through end-use, the energy inputs required and efficiencies at each step dictate the overall energy chain efficiency (Smil, 2008; Tester et al., 2005). In any energyshed with thermal-electric generation present in the energy mix, capturing and using the waste heat potentially doubles the overall energy chain efficiency (Tester, et al., 2005) and makes for sound strategy. In the absence of thermal-electric generation, heat production and distribution for low-quality energy demand can substantially offset high-quality energy demand in the form of electricity. Solar thermal, geothermal, and heat pump technologies are well understood, reliable, and widely available for employment to meet low-quality thermal demands. When considering the efficiency of the entire energy cascade, there is strong argument for investment in "heat utility" infrastructure, as contrasted to investment in adding additional fossil-fuels-based infrastructure (King and Shaw, 2010; Dobbelsteen, Broersma, Fremouw, 2013).

3.8 Information

Information is an essential element to the behaviors of even the simplest systems (Meadows, 2008). Information is generated from the operations of energyshed components and is also a component itself. Losee (1990) produced a discipline-independent definition of information as "the values within the outcome of any process" (p.254). The information system in Shannon's (1948) theory of communication is comprised of: 1) the information source, 2) the transmitter, 3) the channel, 4) the receiver, and 5) the destination. Information signal can be categorized into three types: discrete, continuous, and mixed (Shannon, 1948). From a systems perspective, information is the feedback that produces structure and system behavior (Sterman, 2000). Information as feedback is a critical element and focus of design in development of controlled engineered systems. Patterns in information can exhibit structure including chaotic and fractal patterns (Mandelbrot, 1983). Boundaries, also termed surfaces, develop along strong information gradients (Ahl and Allen, 1996). Alternatively, where information flows readily with little or no information gradient present, the rate of exchange is termed a communications channel (Ahl and Allen, 1996). Communication channels are global while surfaces are local (Ahl and Allen, 1996). The strength of interactions has significant structural implications with higher bond strength and integrity correlated to lower levels of organization as compared to upper levels of organization (Ahl and Allen, 1996). That higher levels of structure dissolve more readily, leaving the lower levels in place, reflects the bond strength differences (Tainter, 1988).

Information development is associated with energy dissipation and particularly as a strategy for mature or maturing systems: "system information increases, which means that the system organization becomes more energetically efficient, typically associated with an increase in genetic complexity" (Jørgensen, 2004). Refined information is required for better system learning to include adaptation and system evolution (Jørgensen, 2004). Technological knowledge and learning required of energy systems decays rapidly if not nurtured, thus demanding persistence and continuity of effort, which also indicates a persistent energetic burden (Grubler, 2012; Tainter, 1988). The structure of information flow affects cooperation and communications among members within a resource commons, with increased communication producing more cooperation, acting to retard the effects of the tragedy of the commons (Janssen, 2013; Hardin, 1968). Delays in information tend to produce system overshoots and oscillations (Sterman, 2000).

Within the energyshed, information is generated from the results of processes, which originate with the operation of the components. Physical signals are the least abstracted and include among others: power signals, energy produced and used, pollution produced and its impacts, infrastructure built or decayed, landscape transformation, and changes in state between components. As an example, information is originated when the energy resource is available, again when power generation occurs, as it is distributed, and then stored or used. Over time, as the power generation-to-end-use process occurs, infrastructure conceivably develops, and land transformation occurs, originating more complex information for the state of the energyshed. Social signal, such as need, resistance, or support, are more abstracted. Even one step more abstracted is market signal to include economic valuation.

Information has a feedback and control function (Sterman, 2000), but it also has a bounding and channeling function (Ahl and Allen, 1996; Holland, 2012). An example of a boundary that affects system behavior would be the tight control over final end-use energy consumption data for stated reasons of privacy, precluding development of accurate patterns of end-use for city-sized units. The lack of consumption information might serve as a deterrent to more informed and involved local government and community action in the local energy commons (Janssen, 2013). Holland (2012) suggests that steering of complex adaptive systems can be effected through modification of signal/ boundary hierarchies. As such, information boundaries both internal and external to the energyshed system are important considerations for informing interventions into the system. The smart-grid is the emerging tool of information flow within an energy system; with properly aligned purpose and surfaces, the smart grid is a promising technology for connecting the energy commons.

CHAPTER 4. ENERGYSHED VALUES

The common elements to the definitions of values found across various fields of study are "concepts or beliefs about desirable end states or behaviors that transcend specific situations, guide selection or evaluation of behavior and events, and are ordered by relative importance" (Schwartz and Bilsky, 1987, p.551). In short, values are a set of preferences, which guide individual and group decision-making and behaviors. Values have a normative role in planning and futuring, and are often related to events that are hoped will transpire in the future (Churchman, 1979). Values can be readily explored through futuring scenarios. Processes such as scenarios futuring serve to clarify thinking and encourage better decisions in the present by testing values through the lens of possible future results of action derived from the value set (Cornish, 2004).

Energy security is a central concept to values associated with energy and it is tempting to frame the value set in the more traditional thinking of energy security. Efforts have been conducted to broaden the traditionally oil-myopic focus of the energy security definition and its applications (for example Brown and Sovacool, 2011). Availability and affordability of energy supplies are the basis for energy security but expanded considerations for energy security include additional dimensions: technology development and efficiency; environmental and social sustainability; and regulation and governance (Sovacool and Mukherjee, 2011). The full set of values associated with the expanded dimensions can be found in Sovacool and Mukherjee (2011). The concept of physical limits and balance are not present within the concept of energy security. So instead I chose an ecosystem perspective to respect the complex nature of energy and its relationships with society, economy, and the environment and to eschew the conceptual structures of the current fossil-carbon-based energy system. In the place of energy security concepts of availability and affordability, concepts such as resilience and interrelationships can emerge.

Consistent with this, I propose coherent, efficient, inclusive, and healthy energyshed as the initial values from which to proceed in design.

4.1 Coherent

4.1.1 Defining coherent

The value of coherence is arguably the most important value for the identification and delineation of a useful functional unit for energy system analysis, to include boundary, function, structure, elements, and relationship. Coherent is defined as forming a unified whole (Coherent [Def.1], n.d.) and as having its parts related in an organized and reasonable way (Coherent [Def.2], n.d.). Coherent evokes attributes of cohesive, coordinated, consistent, integrated, ordered, and structured (Coherent [Def.3], n.d.; Coherent [Def.1], n.d.; Coherent [Def.2], n.d.). A system is more than its parts; the elements within the system and the inter-relationships between them have some measure of coherence, which permits delineation of the grouping as a system.

Coherence of function is integral to the definition of a shed, without which delineation of the shed would not be possible. For example, a watershed where water is imported from distal places would not function as a coherent watershed governed by the hydrological cycle. The thermodynamic coherence of the nature and extents of material and energy flows bring partial definition to an ecosystem; coherence of the adaptive function including adaptation and evolution also illuminate relationships and boundary delineations for an ecosystem (Allen, Tainter, Hoekstra, 2003). A sense of unification and wholeness are present in an ecosystem (Allen, Tainter, Hoekstra, 2003); this is coherence.

4.1.2 Issues of coherence in the global energy supply system

Focus, many resources, and many studies are dedicated to understanding the energy system as a globalized flow of energy from supplier ultimately to end-user. The International Energy Agency (IEA) defines this value as energy security, which is the "uninterrupted availability of energy sources at an affordable price" (IEA, 2015). The term energy security is classically associated with the myopic focus on oil supply lines to OECD nations (Cherp and Jewell, 2014). Structure in this system emerges in the form of tankers, pipelines, and commodity markets to support the function of maintaining availability and affordability of energy flow.

In contrast to the proposed energyshed, the global energy supply system and its closely related value of energy security lack coherence. The coherence of this globalized system lies wholly with the maintenance of a consistent flow of energy but the system enacting the entire energy cycle is not coherent. This system is discontinuous in both space and time. Supply and demand are greatly separated and although there are signals that travel through the flow network that connects them, the signals are weakened and distorted along the way, producing a disassociation between the two ends of the energy cycle, sourcing and end-use. An end-user may have little choice as to what is supplied, where it originated, and who provided it. The user may have little understanding of these details, nor may he have much recourse should he disagree with the provision. Information, including economic signal, do not flow freely up and down the system to facilitate the inter-relationships of a coherently functioning system (Speth, 2008). Cost signal is but one example that fluctuates widely and often not directly as a result of a biophysical or geophysical reason (EIA, 2015a). Sourcing is generally displaced from end-use by taking place in landscapes and social contexts greatly different from the landscapes and social contexts of the end-users. Also, as occurs with a globalized food system, a globalized energy system produces no meaningful boundaries for analysis, management, adaptation and evolution (Kloppenburg et al., 1996).

For a city or municipality engaged in the globalized energy system, there is typically little coherence at all for energy. Efficiency and conservation become the preferred tools with little attention paid to energy capacity building (St. Denis and Parker, 2009). Often, since suppliers and providers operate at higher levels of geographic and organizational scale, there is not an adequate body of data, information, and research collated to the municipality level supporting understanding of energy at this unit. In the old paradigm, the city then functions merely to consume the commodity of energy. A city viewed as such is the equivalent of viewing only the receiving body of water, which terminates the watershed, without acknowledging the relationships in the full hydrological cycle in which production and consumption are linked. This is not an empowered perspective for the city, which might then assume that it must accept what it gets.

There is growing recognition of the incoherence and thus fragility of the current paradigm of the energy system and energy security. Brown and Sovacool's (2011) energy security values exhibit a broadening shift from the more traditional OECD IEA energy security values. Several of their proposed energy security values are similar to the value of having a coherent energyshed, for instance: self-sufficiency, resource availability, security of supply, interconnectedness, security of demand, integrity, predictability, and stability (Brown and Sovacool, 2011). Jewell, Cherp, and Riahi (2014) offer an alternate definition of energy security as "low-vulnerability of vital energy systems," which introduces ecological framing with a systems approach and applies more readily to a wider array of energy systems and system components without the oil-centric and overly narrow constructs of the IEA definition. These shifts in thinking are helpful but do not in themselves create a framework to delineate coherent units of the overall energy system.

4.1.3 Operationalizing coherent

For the most part, a watershed has coherence, barring perhaps occasional subsurface and human engineered flows across the watershed boundary. The land area of the watershed is delineated by its boundary formed at the highest elevations and the land area is contiguous (Schumm, 1977). Within the watershed, gravity and the hydrological cycle driven by sunlight organize the components of the system (Edwards, 2015). That system performs a function to transport water and sediments (Rodríguez-Iturbe and Rinaldo, 1997). The individual components of the watershed and their interactions form a unified whole, the watershed with its own emergent behaviors.

To be a meaningful shed, the energyshed must be a coherent system. A *coherent energyshed has an interrelated set of components; together the components perform the function of the energyshed; an energy community exists within the energyshed; the components, function, and community share a common purpose; from the components, function, community, and purpose emerge a sense of completeness and wholeness.* The components comprising the elements of the shed and their relationships form a larger emergent whole, which has a clear purpose to: *Provide the functions and structure to harvest and dissipate energy to support life, activity, and productivity throughout the energyshed without polluting the environment above its capacity to assimilate those pollutants.* Material and energy flow into, within, and out of the shed. Kloppenburg et al. (1996) characterized the beings within the foodshed as an "eating community" bound together through their need of food and inter-relationships with the system of food within which they live and operate. As with the foodshed, the beings participating in and within the energyhed are bound by their need for energy and the shared system that serves that need. Similarly to the "eating community" sharing common purpose, the energyshed community shares a common sense of purpose to access adequate energy resources. Information fluxes within and across the boundary of the energyshed also define the coherent system and its adaptation and evolution functions (Holland, 2012; Jørgensen, 2004).

4.2 Efficient

4.2.1 Defining efficient

The concept of energy efficiency receives thorough coverage in policy and discourse through all levels of government and in literature. Ecological systems do not waste and so neither can human systems afford to waste (Hawken, Lovins and Lovins, 1999). The importance of efficiency is prominently displayed in national and regional government structures; examples include the United States Department of Energy Office of Energy Efficiency and Renewable Energy, or in the Office of Energy Efficiency of Natural Resources Canada (USDOE, 2015a; NRCAN OEE, 2015). The United Kingdom has integrated its structure and approached the issue directly by combining anthropogenic climate change and energy in the combined Energy and Climate Change Department (UK, 2015). The concept and vernacular of efficiency is adopted in business terminology, increasing numbers of businesses, and industrial ecology practices (McDonough and Braungart, 2002), and there is a developing support industry of equipment, expertise, and standards (Graetz, 2011). St. Denis and Parker (2009) observed that all Canadian municipalities with a Community Energy Plan identified efficiency as a primary strategy for energy-use reduction. They also noted that municipalities approached energy efficiency before energy conservation and that few municipalities ventured so far as to provide for renewable energy capacity development in their strategy (St Denis and Parker, 2009).

The OECD IEA describes energy efficiency as "a way of managing and restraining the growth of energy consumption. Something is more energy efficient if it delivers more services for the same energy input, or the same services for less energy input" (Energy efficiency [Def.1], 2015). The EIA of the United States Department of Energy defined the term more technically as "a ratio of service provided to energy input…energy efficiency provides energy reductions without sacrifice of service"(Energy efficiency [Def. 2, n.d.). When considering the conversion efficiencies of the machines that convert energy to work, the theoretical maximum efficiency of heat engines (e.g. thermoelectric generation plants and combustion engines), the Carnot efficiency, dictates that some heat must be rejected in any practical engine (Feynman, Leighton, and Sands, 1963). The Carnot efficiency is determined by the ratio of the hot and cold temperatures of a working engine cycle (Johnston et al., 1978). Phrased alternatively, the Carnot efficiency is the maximum efficiency theoretically possible given the temperature gradient between the heat source and the heat sink.

4.2.2 Issues with energy efficiency

Energy efficiency is often hailed as fundamental to a post-growth economy (Hawken, Lovins, and Lovins, 1999). Jevon's Paradox infers that the presence of energy efficiency measures will not prove to be a sufficient condition to curb greenhouse gas emissions and the consequent impacts on global climate (Smil, 2008; Jevons, 1865). Counterintuitively, Jevon's Paradox indicates a systemic response to efficiency that results ultimately in increased energy usage, known as the "rebound effect." Increasing trends in energy consumption occurring alongside efficiency efforts support the conclusions of Jevon's Paradox (BP, 2015). Efforts to reduce energy consumption are also confounded by increased demand from Malthusian population increases (as related in Dresner, 2008). Despite its inability to thwart greenhouse gas emissions, energy efficiency certainly appeals as a logical and desired behavior under resource and pollutant assimilation constraints. Not a sufficient condition, energy efficiency might be a necessary condition for development of a post-growth economy and to support an increasing population.

4.2.3 Operationalizing energy efficiency

The thermodynamic theories of far-from-equilibrium open systems developed a basis for a complementary and alternative description of energy efficiency. In this construct, systems, including living systems, produce a state of order, structure, and homeostasis through the influx and subsequent dissipation of energy from and into their environment (Prigogine, 1968; Nicolis and Prigogine, 1977). The existence of an energy gradient is *sufficient* to produce order and structure (Jørgensen, 1999; Prigogine, 1968). As an example from a simple chemical system created by pouring cold creamer into hot coffee, the swirling fractal structure of turbulence produced by heat convection emerge into being to more rapidly dissipate the energy transfer driven by the temperature difference of the two fluids (Glansdorff and Prigogine, 1971). Biological systems are similar. Likewise, human energy systems emerge, to dissipate energy gradients, most commonly at present the energy gradient of available fossil fuel stocks (BP, 2015). In this sense *energy efficiency is marked by the ability of the system to fully dissipate the energy gradient available to it in its environment*. In the presence of an energy gradient, the system will organize to dissipate as much of that energy gradient as expediently as possible, known as the Principle of Maximum Entropy Production, through increased structure and storage until it encounters constraints (Jørgensen, 1999).

Once the system encounters energetic constraints, it evolves through complexification and selection toward minimizing energetic requirements for its own maintenance (Martyushev, 2013).

> Thus, the biomass is maintained at the highest level over a longer time, and the information level will increase because of the steady development of better feedback mechanisms and more self-organization. Both contributions are reflected in a higher exergy. The exergy of the mature system can therefore still grow further, namely by increasing the information. In other words, the system uses its resources better and becomes more fitted to the prevailing conditions (Jørgensen, 1999, p332).

Energetic efficiency in matured dissipative systems, those that have reached constraints, shift toward the classical definition of efficiency as doing more with the same amount of energy. An example is grassland systems in which biodiversity (as an enrichment and complexification of structure) drives productivity increases through more effective utilization of nitrogen, the limiting nutrient (Brock, Mäler, Perrings, 2002). Although dissipative systems do become more efficient with maturation, they do not seek to use less energy (Martyushev, 2013), which is a potential reason why energy efficiency strategies targeting less energy use have not led to reductions in worldwide energy consumption and a thermodynamic explanation to Jevon's Paradox.

Employment of RETs is a generally less matured system that has not yet reached maximum dissipative potential or other constraints. If we evoke the open-systems construct of efficiency as discussed by Prigogine (1968), the criterion for efficiency shifts from the ratio of services produced from an amount of energy expended, or dissipated, to the amount of energy that can be harnessed and expended from that energy flowing into the system. Therefore *energy efficiency is the ratio of energy dissipation in the system to the energy available to the system*. This is reminiscent of the Carnot efficiency, which is based on the ratio of temperatures of the heat source and sink. Developed societies are somewhat efficient at dissipating (consuming) the energy gradient of energy stored in crude oil, as evidenced by robust production to reserve ratios (BP, 2015). Developed countries are to a much lesser degree efficient at dissipating available renewable energy flow, which is primarily the daily solar energy flux of a receiving area (BP, 2015). *An efficient energyshed more fully utilizes the daily solar flux to produce needed services, both human and ecosystem, in the energyshed.*

To expound on this idea, solar radiation is a primary energy source fluxing across a land area such as an energyshed. Much of this energy is either unused or indirectly used, i.e. for heat, biomass growth, the hydrological cycle, etc. Unused solar energy reflects or radiates out of the energyshed. A low ratio of captured energy indicates low system efficiency. Of the captured energy, the extent of utilization, more or less fully dissipated, is the traditional measure of energy efficiency. The expanded definition of energy efficiency does not preclude or contradict the EIA definition of ratio of services provided to energy input; rather, both this and the efficiency of total energy capture must be addressed. An efficient energyshed would have the structure and organization in place to harness and use more of the incoming solar radiation energy flux, as well as other available energy influxes to the energyshed. It would also have the ability to most fully utilize captured energy to best produce more services. Ecosystems accomplish efficiency of capturing energy flux through a rich tapestry of multi-level organizational structure, biodiversity, and energy cascades to capture energy at as many niches as possible. An efficient energyshed would have the same.

4.3 Inclusive

4.3.1 Defining inclusive

Inclusive is defined as "Including all the services or items normally expected or required; containing (a specified element) as part of a whole; not excluding any section of society or any party involved in something" (Inclusive [Def.], n.d.). Inclusive is also defined as "Including everything or all types of people" (Inclusive [Def.2], n.d.). Two themes emerge from these definitions of inclusive. First, to be a coherent whole, all of the appropriate parts must be included. Second, to be inclusive, all individuals and groups in the community must be included.

4.3.2 Issues for energy system inclusion

Currently, inclusion in energy systems, from the perspective of "all appropriate parts," is quite varied. Energy systems with heavy reliance on large multi-national corporations, which exert some semblance of control from the beginning to the end of the supply and distribution chain, would seem to be on the far end of the scale representing less inclusion. The cost of organizing so many of the components in the energy supply and distribution chain under a single large organization is a loss of diversity in each functional area and at each organizational level. I contend that the result is a sparsely populated energy dissipation system in that many niches remain unpopulated and energy flows, specifically renewables, remain unutilized. Conversely, on the other end of the spectrum, a more inclusive system would have a diversity of forms, sizes, and types of energy systems within the energyshed. Ideally the variety would fill more energy niches across multiple levels of scale to make best use of all available energy flows, increasing the energyshed efficiency per the definition above, and also conceivably enabling more inclusion and participation of the community involved.

Many energy resources "reside" in the commons and the impacts of their use are also resident in the commons, bringing heightened need for community inclusion in decision processes (Ostrom and Dolsak, 2003). Community inclusion in decision-making and even ownership structure can enhance stewardship and reduce friction, such as Not-In-My-BackYard sentiment (Hester, 2008; DeYoung and Princen, 2012; Dolsak and Ostrom, 2003). Participatory engagement processes tend to enhance chances of overall successful natural-resource-based projects as compared to those done without public involvement (Lynam, de Jong, Sheil, Kusumanto, and Evans, 2007). Legitimacy from consensus and the vesting of participants results in intrinsic commitment, and strong social pressures, to implement decisions (Tainter and Crumley, 2007). For diffusion and acceptance of new technologies, public engagement can foster trust building and reshape the trajectory of technology uptake (Gardner and Ashworth, 2008). Renewable energy sources tend to be distributed, such as solar and wind, and so will likely be highly integrated into the urban fabric and surrounding landscapes in a distributed or dispersed grid scenario. The strong linkages between energy and other land-based critical resources, such as food, biomass-derived products, development area, and clean water, for example, are likely to intensify, as renewables become a larger share of energy portfolios (Graedel and van der Voet, 2010).

Three categories of barriers to sustainable change are understanding, political will, and capacity building (Gunderson and Holling, 2002). Community inclusion in complex governance decisions for which the community is a substantive stakeholder has a clear role in addressing each of these categories of barriers (Hendricks, 2010). As such participatory planning is a well-established practice for generating solutions for complex problems in the social sphere (for example Berkes, Colding, and Folke, 2003; Gunderson, Holling, and Light, 1995). Values are often identified through a participatory engagement process, which is a well-established practice in fields such as resource management as well as urban design, and is becoming more frequent in the energy field (Lynam, et al., 2007; Gunderson, Holling, and Light, 1995; Hester, 2008).

4.3.3 Operationalizing inclusive

Continuing with the non-equilibrium-thermodynamic system argument, an energyshed would become more inclusive as capacity to capture energy fluxes increased through the evolution of an energy ecosystem more fully and diversely populated at each level and in each niche. *An inclusive energyshed fosters diversity of components and sizing, seeks equity within the community, and seeks to fully populate the energy system to best conduct the function of the energyshed to resource, generate, distribute, store, and dissipate energy.* Scavengers and decomposers in the field of industrial ecology are the partial equivalent and an example of diversity; in this case smaller scavenger and decomposer organisms fill available energy niches (Geng and Cote, 2002). More inclusion should then produce a more efficient energyshed. Complexification of social structure increases energy harvesting efficiency (Hamilton et al., 2007) and that complexification comes with an energetic cost (Tainter, 1988). A stable middle ground will need to be found, as will an appropriate balance between technical knowledge and participatory democracy (Hendricks, 2010).

4.4 Healthy

4.4.1 Definition of healthy

Healthy is defined as "In good physical or mental condition; not diseased; indicating or promoting good health; normal, natural and desirable; of a very satisfactory size or amount" (Healthy, n.d.). The World Health Organization (1948, p. 100) promotes a more encompassing and proactive definition, "Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity." In the society-in-the-environment model of ecological economics, the health of society is not possible without the health of the ecosystem. In a "full-world", accumulation of wastes and degradation of ecosystem capacity to produce resources and ecosystem services can no longer be ignored in terms of human sustainability (Daly, 2015). The biosphere is severely threatened by current methods and scale of energy production, for both food and fuels; this is the single most important driver of ecosystem degradation (Millennium Ecosystem Assessment, 2005).

4.4.2 Issues of energy system health

Energy system impacts on human health and sustainability have been well studied. Extraction, processing, generation, and pollutant release associated with the energy sector is responsible for both macro-environmental impacts such as anthropogenic climate change and ocean acidification, and local impacts such as pollution run-off into local water bodies or reduction of local air quality for instance (Millennium Ecosystem Assessment, 2005). These impacts systemically diminish future potential for human health and constrain future economic capacities (Robert, Daly, Hawken, and Holmberg, 1997). Human populations are constrained by energetics as are all other animal populations (Moses and Brown, 2003) but have currently exceeded energetic limits (Wackernagel et al., 2002) for fossil fuels and through such have produced perverse damages to the biosphere (Daly, 2015).

The preponderance of deployed energy systems today are not healthy systems and exhibit frailty and infirmity along multiple dimensions. Energy systems do not exhibit adequate diversity across multiple levels of scale as discussed above. As an example, local energy production is not well represented in favor of concentrated and often distant production (BP, 2015), increasing vulnerability and reducing capacity for adaptive reorganization. The current energy system is not resilient, nor vigorous, as it operates at or close to capacity (Willis and Scott, 2000). Disturbances can have widespread catastrophic effects such as the Northeast Blackout of 2003 which affected more than 10% of the combined population of the United States and Canada and left most without electricity for days and some for several weeks (U.S-Canada Power System Outage Task Force, 2006). Rigorous integrated life-cycle assessments have determined unambiguously that the most effective decarbonization strategy is to stop using fossil fuels and shift to renewables; the analysis included changes in required infrastructure for renewables (Hertwich et al., 2013; Weisser, 2007; NREL, n.d.; Pehnt, 2006).

4.4.3 Operationalizing healthy

A healthy energyshed is able to meet the purpose of the energyshed, which is to produce adequate energy without accumulating pollutants. Costanza and Mageau offer a succinct and convincing definition of ecosystem health:

> We propose that a ‘healthy’ system is one that
> can develop an efficient diversity of components and
> exchange pathways (high organization) while maintaining
> some redundancy or resilience as insurance
> against stress, and substantial vigor to quickly recover
> or utilize stress in a positive manner. " (1999, p109)

Conversely, an unhealthy ecosystem is not sustainable and so will not achieve maximum (expected) lifespan (Costanza and Mageau, 1999). The three components of ecosystem health are: 1) vigor, a measure of activity, metabolism or primary productivity; 2) organization, the number and diversity of interactions among components of the system and diversity of species and material exchange pathways; and 3) resilience, the time to recover and magnitude of stress from which recovery can occur (Costanza and Mageau, 1999).

The operational definition of healthy for the energyshed must consider health for the energyshed community of people to include physical, social, and mental well-being. The health of people is linked to the health of the ecosystem in which they live, so pollution must be included in the accounting. The definition must also consider a healthy energy ecosystem that is diverse, resilient, and vigorous. *A healthy energyshed provides adequate energy for the embedded community without accumulating wastes or impacting the well-being of the community; a healthy energyshed system is diverse, resilient, and vigorous.*

CHAPTER 5. THE PRINCIPLES OF ENERGYSHED DESIGN

The complexity of the system of energy within an energyshed dictates that a rigid and algorithmic approach will not be capable of characterizing, adapting, and providing adequate insight to constructively engage in management interventions into any but the smallest and least connected energy system. A more flexible and evolving approach is needed and so guiding principles were developed herein to codify important design considerations for development and intervention into the design and management of the energyshed. A principle is defined as "A fundamental truth or proposition that serves as the foundation for a system of belief or behavior or for a chain of reasoning" (Principle [Def.], n.d.). Principles are often developed in an attempt to increase unification in a body of scientific work or practice (National Research Council, 2002). As an example of application, McDonough (1992) proposed the Hannover Principles for the sustainable design of World Expo 2000. The Hannover Principles were intended to provide a framework to guide, inform, inspire an approach, evolve with changing circumstance, and form the "foundations of a new design philosophy" (McDonough, 1992). Those principles have lived beyond their original intent and served as an early and enduring assemblage of an integrated sustainability design framework for the built environment.

The principles of energyshed design are grounded in the established sciences of ecology, hydrology, and thermodynamics. In the wake of Prigogine's (1968; Prigogine and Glansdorff, 1971) development of the understanding of structure as the result of dissipation of energy, the theories of thermodynamics of open dissipative systems have been applied to the disciplines of ecology and hydrology. For example, Rodríguez-Iturbe and Rinaldo (1997) hypothesized that drainage basin channel development was self-organized around the principle of minimum energy dissipation, producing flow structure seeking minimal energy for structural maintenance and resulting in fractal drainage basins. The theories of dissipative non-equilibrium thermodynamics have also been incorporated into the discipline of ecology to unify previously unlinked energetic behaviors of ecosystems such as a tendency toward maximum energy dissipation for the overall system (Jørgensen, 2004).

Several of the ecological principles noted by Jørgensen (2004) and viewed through the lens of the thermodynamics of dissipative systems provide an interesting analogy to the "ecosystem" of the energyshed and I will apply them to the development of the design principles of the energyshed. Considered first, the energyshed, as a reflection of human energy conversion and dissipation, is an open system embedded within its environment with which it exchanges energy and materials. Containing an energy ecosystem, a coherent, efficient, inclusive and healthy energyshed will have many levels of organization, hierarchically arranged. An energyshed contains many components but at minimum the two primary roles of energy fixing and then decomposition and recycling are required. The structures, such as buildings, energy systems, and knowledge created by energy dissipation, can at times decay. The decay releases both embedded energy and the requirements for maintenance energies, making some of this exergy available for new growth or maintenance of other structure and ordering. As a reminder, exergy is the portion of energy available to produce work. All of these exchanges follow the 2nd law of thermodynamics and are therefore irreversible and increase total entropy while decreasing total exergy in the universe.

Two more points from Jørgensen's (2004) work are worth discussing before presenting the principles of energyshed design. Jørgensen (2004) suggests that the results of energy dissipation by living organisms are one or more of 1) increased physical structure (biomass), 2) increased network (more cycling), and/or 3) increased embodied information (configuration). The first enables increased energy capture from the environment and the second and third produce increased efficiency of utilization of the captured fraction of energy. In the presence of available energy, the system moves away from thermodynamic equilibrium by increasing stored exergy and increasing energy throughflow in the system

(Jørgensen, 2004). The process tends to proceed according to the hypothesis of the 4th law of thermodynamics:

> If more than one pathway to move away from thermodynamic equilibrium is offered, the one yielding the most stored exergy under the prevailing conditions, that is, with the most ordered structure and the longest distance to thermodynamic equilibrium, will have a propensity to be selected (Jørgensen, 1999, p339-240).

Certainly from the perspective of the linkages between gross domestic product, energy use, and development, this would seem to hold at least anecdotal truth for human energy systems. The principles discussed here suggest that, with the exception of occasional inputs of stored energy, the solar insolation received into an area is the ultimate limiting exergy capacity and one that should therefore be considered sooner rather than later in energy planning.

The following principles are proposed to guide the design of an energyshed. They were developed to respect the principles of sustainability, land-use planning, thermodynamics, complexity, and ecology. The intention of the principles is to encourage energy system coherence, efficiency, inclusion, and health. The five principles of energyshed design are to: 1) maximize use of renewable sources; 2) strive for the smallest possible energyshed; 3) apply units of power instead of energy; 4) enhance diversity; 5) encourage broad participation in the energyshed.

5.1 Maximize exploitation of renewable energy resources

For the least environmental impact, all production should be from RETs.

As an energy resource, the combustion of fossil fuel is constrained by carbon dioxide pollution in the short term and supply in the longer term. RETs may eventually face localized or regional constraint from land space requirements but not in the foreseeable future. The exception may be biofuels from terrestrial agriculture because of their direct conflict with food production and low production energy intensity. RETs are at an early stage in which the system tends toward increasing physical structure through increased RET infrastructure development for energy capture. Later-development, such as that currently for the conventional fossil fuels system, show increased networking and complexification of information, thus facilitating increased efficiency. The distribution of renewable energy flows is more geographically distributed than fossil fuel and all regions have untapped RET capacity available to them. Given the broad geographic availability of the high-quality solar radiation energy resource, the behavior of a non-equilibrium system, which human social systems are, would lead to rapidly increased infrastructure to capture solar-based energy flows. A review of barriers to increased solar flow capture may reveal obstruction by existing but dated fossil-fuel energy infrastructure nearing the end of its usefulness.

5.2 Strive for the smallest possible energyshed

To increase energy capture and utilization efficiency, the energyshed should be as small as possible.

Creating the smallest possible energyshed implies efficient integration of energy production with other land uses. A smaller shed area is more likely to be within the governance of the local municipality or county, simplifying planning (to include planning for energy storage) and increasing local self-reliance. A smaller energyshed co-locates more of the energy-related impacts and benefits within the local community, enhancing and balancing feedback loops and community communications (Scheer, 2008; Janssen, 2013), and fostering conditions for improved inclusion and stewardship of the energy resource system in the energy commons (Olstrom and Dolsak, 2003).

5.2.1 Improved energy capture efficiency

As the area of the energyshed increases, the total capture efficiency for the shed decreases since average power production density within the shed will at some point decrease. As the shed boundary increases beyond the densely populated urban core and moves into the hinterlands of the city, power end-use density will drop while power generation capacity density will increase until an optimum capture efficiency is reached. "Energy sprawl" should be avoided to minimize ecological disruption by energy infrastructure. A tension between minimizing size for management, efficiency, and ecological issues and generating enough energy may exist. This may be especially pronounced given the current tendency to shift power generation away from population densities, although rooftop PV and solar thermal system employment in the urban core are challenging this paradigm.

5.2.2 Utilization efficiency

In addition to the social and systemic advantages identified above, a smaller energyshed will require less infrastructure, potentially eliminating part of the financially and energetically costly transmission side of the transmission and distribution system (Roadstrum and Wolaver, 1987). Losses across the entire transmission and distribution system in the United States averaged 6% from 2004 to 2013 but are substantially higher in regions relying on power from afar (EIA, 2015b). Transmission losses are a significant concern and reduce the overall efficiency of the electricity system (Willis and Scott, 2000; Volk, 2013). Transmission systems are expensive and many in North America are in need of refurbishment or replacement (USDOE, 2002; Volk, 2013). Increased transmission loss, increased risk of damage, increased costs for infrastructure, and increased operation and maintenance costs are related to increasing path-length of transmission and distribution. Fractal form defines the limiting ideal for efficient distribution (Schroeder, 1991) embodying least cost and least loss, with maximum connectivity through space with minimum path length (Rodríguez-Iturbe and Rinaldo, 1997). Fractal form distribution can be used as a planning and design benchmark. The tension between efficiency and effectiveness must also be considered and so some path redundancy, in the form of a network, may be important for critical services, although overall vulnerability is generally reduced in a widely dispersed energy grid. To extract the most exergy from captured energy, reusing waste heat and matching energy end-use requirements to the lowest acceptable quality of energy available will improve utilization efficiency. Finally, utilization efficiency also requires demand reduction per service used through classical efficiency measures familiar to the current industry.

5.3 Apply units of power instead of energy

To appropriately characterize temporal behaviors of the intermittent renewables and variability in user demand, power should be the primary dimension of analysis.

RET energy production is characteristically intermittent with timing around the minute to hour level of time scale. So, although aggregated energy averages in and out of a system are valuable for understanding larger-scale impacts and balances, they are inadequate on their own to inform design and operations of renewable-based energy systems. Power is the derivative with respect to time of energy, or energy at an instant. Observing and modeling power is useful for fully understanding the intermittency of RET within the energyshed and the dynamic relationships between RET production and consumption in the energy network. Differences between the two through time can be studied to identify the requirements for storage capacity and inform the design parameters for generation, end-use and storage systems embedded within the energyshed. Although utilities are familiar with power as a unit of analysis when balancing the operation of electrical grid and power plants, government-level planning products for energy are not crafted in units of power and so do not benefit from an understanding of the intermittency inherent in many renewable generation systems. This is also not to say that using the dimension of energy should be completely abandoned, as energy balancing can provide useful estimates of system performance over time, but some important system characteristics and limiting conditions will be lost through time averaging required of the energy dimension.

5.4 Enhance Diversity

To increase resilience of the energyshed, portfolios should include a diversity of RET energy producers and end-users, and near power-law distributions of size for each.

5.4.1 Varied generation and end-use

Resilient ecosystems exhibit diversity of organism composition and function (Costanza and Mageau, 1999). Employing a variety of RET-based energy generation and storage systems will ideally fill more niches of those available within the energyshed. Similarly, a variety of end-uses and cycle times of each will provide added flexibility for demand-side management when power-balancing within the energyshed. Resilience demands excess production capacity, which further supports reasoning for supply-side diversity so the burden of maintaining excess capacity is dispersed throughout the system. In a centralized system, the demand-side is dispersed and not the supply-side, which is a gross imbalance (Grubler, 2012).

5.4.2 Size distribution

Resilient systems exhibit multi-layered and hierarchical organization, and near power-law structural forms for that organization (Schneider and Kay, 1994; Yakimov, Solntsev, Rozenberg, Iudin, Gelashvili, 2014). Power-law, or fractal, scaling is a fingerprint of structure and organization resulting from energy dissipation and also represents an ideal efficiency in distribution (Yakimov et al., 2014; Nicolis and Prigogine, 1977; Bak, 1996). An energyshed, as a dissipative structure, should exhibit near fractal form, even if lumpy, in multiple dimensions and, in specific, size distribution of the constituent "organisms" that participate in the energy dissipation within the energyshed (Laurienti et al., 2011). In this case the obvious participants are energy generators, distributers, storers, and end-users. Size distributions of energetic systems found in nature, such as a foodweb, have fewer larger and more highly organized entities and many smaller and less highly organized entities. The diversity of locally employed RET mixes and organization from energyshed to energyshed could also improve regional energy stability and foster a broader collective knowledge base concerning energy systems and solutions.

5.5 Encourage broad participation

To increase self-organization and systemic restructuring within the energyshed, broadly increase participation in all aspects of the energyshed.

The capacities to adapt and evolve are characteristics of resilient systems (Gunderson and Holling, 2002). "Too big to fail", a descriptor often used to characterize the centralized nature of petroleum production and distribution, does not infer resiliency, but rather vulnerability of catastrophic magnitude for the system. Structural re-alignment is necessary since shoring a naturally vulnerable system is only to delay the inevitable grand disruption that crumples the system (Werner and McNamara, 2007). In the relatively open field of RET employment and capacity building, a municipality has the opportunity to actively promote restructuring by developing methods to broadly increase participation in energyshed functions. Energy democracy as a form of self-organization is the limiting ideal, although the continuum between centrally controlled energy and energy democracy is the operating region in which various energysheds can explore the best fit for their specific cultures and circumstances. Typical municipalities and the constituents within an energyshed already have reasonable latitude to effect greater direct participation in the energyshed. More can be designed with creativity and intention. As with many other self-organized systems, such as magnets, getting the first few parts aligned within the energyshed may be enough to coax the remainder to re-align.

CHAPTER 6. CONCEPTUAL AND PRACTICAL IMPLICATIONS: ENERGY MAPPING

6.1 Energy cartography

Energy cartography has the potential to fill the vacancy for an integrated energy planning, policy development, and civic engagement tool that is needed for energy system transition to renewables. Modern computing capability, the infrastructure of GIS, and increasingly available data sets enable advanced mapping tools suitable for decision support. Historically, energy cartographers from the early twentieth century prominently represented political boundaries, almost entirely at the national level, and predominantly mapped large infrastructure projects, such as hydroelectric dams (Howell and Baylis, 2014). Energy mapping in the 1980s reflected national level preoccupation with fossil fuels and energy security thereof; energy cartographers of the 1990s and 2000s introduced social issues of energy and also perceived risks associated with energy (Howell and Baylis, 2014).

Energy mapping today is migrating away from the static, non-interactive, national-level only, and fossil-fuel-centric mapping tools and products of the near past, and a new array of maps now model renewable energy. Santos et al. (2014) offer that solar potential, but also more broadly applicable to other RETs, can be categorized into three distinct categories: 1) physical potential (resource characterization), 2) geographic potential (location-specific potential), and 3) technical potential (equipment capture and conversion characteristics). For physical potential, national and regional mapping resolution is appropriate, adequate, and existing for many parts of the world and so I will not develop it further in this thesis. The third, technical potential, informs specific machine performance. The middle category, geographical potential, is where I will focus since energy mapping is currently evolving most here and has the potential to develop into an integrated multi-source model for municipal-level energy strategy, planning, and design.

Energy cartography offers a uniquely important method of communicating energy issues. Energy mapping serves a critical need since energy, and its important linkages, is a complex subject and one that endured distorted messaging at the whims of powerful interests (Hoggan and Littlemore, 2009).

> The cartographic act solidifies the object of study, making it tangible and permanent even if, as in the case of water networks or raw fossil-fuel resources, the object itself is relatively invisible to the general public and somewhat uncertain to scientists and other decision makers" (Howell and Baylis, 2014, p212).

Maps serve as a communicative tool and also as an object of material and intellectual culture (Howell and Baylis, 2014). Energy cartography has the following specifically relevant set of capabilities, ordered in a loose hierarchy:

1. Effective public engagement, communication, and education platform
2. Quantification of the maximum technical potential of renewable energy production
3. Identification of spatial patterns of energy flows and infrastructures across the land area of the analysis
4. Spatial integration of different types of renewable (and non-renewable) energy sources and their impacts across a range of spatial and temporal levels
5. Full integration of energy into urban spatial planning as an entering argument and not as an after-thought
6. More-advanced mapping can provide a model with which to observe and analyze emerging system behavior patterns that will occur with mixed-renewables-dominated systems.

No other single tool offers such a relevant and broad range of modeling capacity for energy systems, nor one so flexible, which also uses infrastructure that is already in widespread use. Top-down forecasting methods are not worthy of the task to guide energy transition (Lovins, 1976; Robinson, 1982; Schwartz, 1996). Energy mapping is the principal tool of RET planning and energy cartography can evolve to more fully meet the needs of energy planners at the municipal level.

6.2 Solar mapping

Solar mapping has been the most dynamic focus for energy mapping in the last decade. LiDAR-derived data have become more widely available and with them solar shadow techniques for applying the high-resolution data to solar-insolation modeling, with roof contour detail for individual buildings (Jakubiec and Reinhart, 2013). There is a variety of other estimation methodologies including building-stock type, rooftop area estimates from block-type data, and hybrid models incorporating several of the above methods (Kucuksari et al., 2014; Santos et al., 2014; Wiginton, Nguyen, and Pearce, 2010; Khanna, Jenkins, and Niemeier, 2010). For further reading, Jakubiec and Reinhart (2013) provide a useful survey of solar potential maps and specific solar mapping techniques in North America, and Calvert et al. (2013) provide a fairly comprehensive and insightful review and analysis of RET mapping using remotely sensed data.

The recent trends in solar mapping have shifted from identification of existing renewable infrastructure towards more accurate modeling of solar potential, city-level and smaller focus, and more-engaging interactive features within the map (Table 4). Mapping with improved solar accuracy (Jakubiec and Reinhart, 2013) has seemingly displaced multi-source integration as was attempted in San Francisco with a wind overlay over the solar layer a few years before (City of San Francisco, n.d.). High-resolution energy consumption information is not integrated into any of the maps, which portray energy production potential, and in general non-aggregated consumption maps are rare and only estimates given tightly controlled access to these data (Howard et al. 2012b).

Privacy policies and practice often protect the privacy of polluters at the cost of the commons, which is no small point, and one that is of significant hindrance to integrated energy modeling for cities. The need for access to non-aggregated consumption data for integrated mapping of supply and demand is a common theme in the field of energy mapping (Domínguez and Amador, 2007; Calvert et al., 2013; Howell and Baylis, 2014; van den Dobbelsteen et al., 2013).

The introduction of impacts into energy mapping was developed in the "energyscapes" concept by Burgess et al. (2012) and Howard et al. (2012a), which integrated estimated energy production impacts on ecosystem services for the Marston Vale, England, a small municipality-sized area. The map incorporated several dimensions of ecosystem goods and services with energy production, to include food, animal feed, urban development, and forest products. Integrated models are possible but infrequently created. Finally, it is worth noting, that all the maps presented below are modeled to the extent of their data set and/or the extent of a political boundary. The question of appropriate extents for analysis when producing energy maps remains an item for debate (Calvert et al., 2013), but the default position has been the political boundary when not otherwise constrained by data extent limitations.

6.3 Wind and other energy mapping

Wind energy mapping has developed differently than solar energy mapping. The primary enabling data required for wind energy mapping are the wind resource grids. Wind resource models are typically produced in tabular and map format at the national level resolved to tens of kilometres (for example NREL, n.d.; Environment Canada, 2003) and are less frequently available at higher resolution (hundreds of metres) at regional level (EERE, 2015; Nova Scotia, n.d.). Since wind interacts with terrain, wind speed varies significantly with small changes in altitude above ground requiring vertical differentiation. This is usually generated at several steps corresponding to typical industry standard turbine hub heights from 30 metres for small turbines to 100-110 metres above ground height for utility-sized turbines, and now at 130-140m heights for projected turbine size and height increases (NREL, n.d.). Wind resource maps are created from historical wind measurement including direction, magnitude, and timing. Extrapolation of measurement data, terrain modeling, and fluid computation dynamic modeling techniques are used to populate the interstices. Time series data are now available for in-situ wind energy systems and so although time-specific performance is stochastic, statistical and forecast models can provide reasonable time-series data for power behavior modeling.

Table 4. Key features of current energy maps

Key feature or characteristic	Map example
Existing RET installation	New York Solar Map[1]
Existing energy infrastructure	London Heat Map[2]
Nexus for relevant information for renewable projects	San Francisco Solar Map[3]
Mixed renewable energy sources	Capay Valley Energyshed[4] San Francisco Solar Map[3] Energy potential mapping[5]
Energy consumption (city-block-level resolution)	Estimated: Total Annual Building Energy Consumption for New York City (Howard et al., 2012b)[6]
City-wide coverage with building-feature-level resolution	Cambridge Solar Map [7]
Site specific finance-energy calculators	Cambridge Solar Map[7]
Interactive public interface	Cambridge Solar Map[7]
City-wide energy potential statistics	Cambridge Solar Map[7]
Impacts on other resources	Energyscapes (Burgess, Howard, 2012a)[8]
Boundary: extent of data set and/or political boundary	All above

([1] New York City, n.d.; [2] Mayor of London, 2010 ; King and Shaw, 2010; [3] City of San Francisco n.d.;[4] Khanna, Jenkins, and Niemeier, 2010; [5] van den Dobbelsteen et al., 2013; [6] Howard, Parshall, Thompson, Hammer, Dickinson, and Modi, 2012;[7] Mapdwell, n.d; Jakubiec and Reinhart, 2013; [8] Burgess et al., 2012; Howard et al. 2012a)

Wind production sites are generally identified from the coarse grids of the national or regional wind maps. Several sites may then be identified for detailed analysis including wind measurement studies on site. Once selected, specific site(s) design modeling decision aids, such as Openwind, can be employed to develop the turbine performance and interactions among planned turbines for developer-level project planning (Openwind, n.d.). This process appears adequate for utility-level wind project development as turbines are populating the landscape with increasing regularity in North America, Europe, and China. Municipal-level planning tools are developed only to the anecdotal level across a municipality (for example City of San Francisco, n.d.) or for specific projects, and so do not provide a refined estimate for the wind energy generation potential for the municipality, nor in most cases direct interactions with other energy sources.

Some works linking energy to mixed-source interactions and ecosystem goods and services impacts have been conducted. Monforti et al. (2014) investigated the interaction between RETs, the complementarity of solar and wind in this case, across Italy with a 4 km-by-4 km grid and in the context of the national energy demand profile. They found synergies in their scenarios with the employment of a mix of solar and wind RETs (Monforti et al., 2014). Further developing mixed energy source interactions in a spatial model is a promising method, which will become more important as RET deployment density increases. Wind energy planning tools for the municipal energy manager are sparse. Many case studies employed multi-criteria decision analysis (MCDA) mapping techniques using regional-level data to develop wind-energy feasibility maps for a region the size of the Bay Area of San Francisco, for example (Rodman and Meentemeyer, 2006; Tegou, Polatidis, and Haralambopoulos, 2011; Janke, 2010). This is a valuable tool for regional assessment. The resolution was not adequate for detailed energy planning for wind energy; the MCDA technique with higher resolution data would certainly inform municipal-level wind-zoning decisions. Alternatively, Hsieh and Fu (2013) conducted rooftop and small-turbine wind modeling with computational fluid dynamics methods for a coastal city in China with results suitable to inform small-turbine placement within an urban context. The combination of the two methods may hold some promise for municipal-level wind energy modeling.

MCDA mapping analysis, for the energy maps of the Dutch province of Groningen as an example, offers a partial solution to the integration of multiple sources and identification of best sites for RET (Van den Dobbelsteen et al., 2013; Khanna, Jenkins, and Niemeier, 2010; Burgess et al., 2012). The Rotterdam Heat Map and Marston Vale Energyscape norm energy to a single consistent unit, GJ/ha heat and kWh/person-day in the first case modeling available heat and demand across the city and annual energy production capacity versus other needed ecosystem services. Van den Dobbelsteen et al. (2013) broach the concept of the available "heat supply fills the resulting sink" (p. 77). Both models beg the question of going a step further and creating a single unified energy surface suitable as an energy surface for robust analysis.

6.4 Current issues in energy cartography and geo-information infrastructure

6.4.1 Missing elements of energy cartography

As the world eschews fossil fuels, the advent of the global energy system transition to RET presents new challenges for the field of energy cartography. The need for improved integration within map products is a dominant theme. This integration includes mixed energy sources, consumption-and-production, and synergistic co-land-uses for energy-to-energy and energy-to-non-energy applications (Domínguez and Amador, 2007; Calvert , Pearce, and Mabee 2013; Howell and Baylis, 2014; Resch et al., 2014). Domínguez and Amador (2007) suggest creating a regional integrated vision with all energy system variables integrated in a model of decentralized electricity generation. Howell and Baylis (2014) observe that access to reliable consumption data is almost entirely unavailable at local levels where consumption actually occurs, confounding the modeling of the coupling between consumption and production of energy at a reasonable integrity.

Historically, reference has been precedent over analysis leaving many energy cartographic products less insightful than otherwise possible (Howell and Baylis, 2014). North America and Europe still benefit from the predominance of energy maps (Howell and Baylis, 2014). The rest of the world seems to be closing the gap for broad-area renewable resource maps and in some cases detailed local analysis of renewables, especially in countries increasing employment of RETs (for example Byrne et al. 2015; Hsieh and Fu,2013). Given the generally accessible cost of basic mapping products (Murray, 2012), the value and utility of even very basic renewable energy mapping products, and the growing library of versatile data sets owned and/or available to local government, I would expect to see substantial growth in energy mapping concurrently with the growth of RET employment.

Energy mapping can mitigate uncertainty and build general capacity for renewable energy policy, decision-making, and employment (Calvert et al., 2013). This is to say that building the geo-infrastructure to include data, knowledge, organization, methods, and hardware, is of importance to the capacity for RET transition and the planning, design, and operations thereof. Building this capacity is not single-purposed and should align with a wide array of other municipal planning process. Four underdeveloped energy-mapping-research areas for building energy-geo-infrastructure institutional capacity are: 1) resolving issues of scale level and in particular identifying appropriate extents of analysis; 2) developing processes to map interactions of mixed-source energy systems; 3) applying energy resource maps as primary input for development of technology roadmaps; and, 4) identifying priority areas for RET deployment including social and environmental factors (Calvert et al., 2013).

6.4.2 Recommendations to evolve energy mapping

In addition to those above, I offer a few additional thoughts for the evolution of energy cartography. First, no map that I have encountered to date has considered the basic nature of renewables as both variable and intermittent. Average annual energy production is a gross simplification that neglects the issue of variability and intermittency. To observe the temporal characteristics of renewables, the time step must be small enough to observe the substantial fluctuations of the most volatile energy resource in the energyshed. This means power must be modeled in lieu of or in addition to energy, which is time-averaged. This is a critical element to creating an integrated spatial and energy system model.

Second, there is a need for an energy model that provides a single, integrated, and high-resolution energy surface for mapping analyses. For renewables, this model could be a power surface, which delineates power production, power consumption, and the difference to create the net power surface. The highest resolution of the map needs to support individual producer/consumer decision-making, and thus also encourage interactivity with the map at the individual-level (Howell and Baylis, 2014). For solar mapping this implies roof-top-feature-level resolution such as typical for, but not solely relegated to, LiDAR-based solar mapping. It also implies relevant information to aid decision-making for RET employment, such as production cycles and performance, cost, zoning and siting, government programs, other local installed systems, and some glimpse into impacts and benefits to the community through individual decisions.

Finally, much debate still occurs as to the optimum boundary of analysis (Calvert et al., 2013). Hughes (2009) departs from the political boundary default and suggests grid-operation regions or market regions indicating that utility organization or market organization is an appropriate unit of energy system analysis. Calvert et al. (2013) propose 3 principles for identifying regional boundaries for renewable energy purposes: 1) the unit of analysis should be politically contiguous, 2) take advantage of relevant economies of scale for such as base-loading for example; and, 3) capture a heterogeneous landscape capturing multiple energy resource options.

I generally agree with Calvert's point three but I contest point one and part of his second point, as well as Hughes' organization to existing market and switchboards. Although it seems appealing to leverage the existing political and/or market organizational structure, the tendency to do so masks the nature of the energy system and presses it into the political or market structure. Annila and Salthe (2009) argue that economic activity is the resultant emergent structure from energy dissipation. This is consistent with non-equilibrium thermodynamics (Prigogine, 1968; Nicolis and Prigogine, 1977). To restate this, economics and politics are neither sufficient nor necessary for energy dissipation, but the physical phenomenon of energy dissipation is the necessary, and arguably single sufficient, condition for both economic and political activity. Analogously, watersheds are organized around the biophysical phenomenon of the hydrological cycle (Leopold et al. 1995) and so analyzing a watershed to political extents would be nonsensical. Both points indicate that the organizing principles of energy, grounded in the physical phenomenon and in this case renewables-dominated energy systems, should lead the discussion of subsequent organization, such as extents of analysis, markets, and grid structure. This begs the question of a fundamental land unit of energy and how it might be identified.

There is clear need for an integrated spatial-energy model to increase capacity for renewable energy system planning, decision-making, and system operation (Resch et al., 2014; Calvert et al., 2013; Howell and Baylis, 2014). The phenomenon of energy and, specifically renewable energy, must be the central theme and not other constructs such as markets, political organization, or economic consideration; these are higher levels of abstraction and will follow from the physical phenomenon. Identifying the "energy terrain" of the energyshed requires a new data model.

6.5 Mapping energy terrain: the digital power surface model (DPSM)

6.5.1 DPSM definition

The digital power surface model (DPSM) is proposed as a data model to represent the "energy terrain" from which to delineate the energyshed. The basic data structure of the DPSM is a raster, or two-by-two array of cells, which is a commonly used data model for terrain analysis (de Smith, Goodchild, and Longley, 2009), because of its simplicity, efficiency, and utility for analysis (Jordan, 2007). Rasters best represent continuous features as opposed to discrete features, which is suitable for representing spatially distributed power production and end-use across the energyshed (Bolstad, 2008). The digital elevation model (DEM) is defined as "an ordered array of numbers that represent the spatial distribution of elevations above some arbitrary datum in a landscape"(Jordan, 2007, p17). The DEM is the simplest form of a digital terrain model (DTM), which is an ordered array of data that represent spatially distributed terrain features, and is used routinely in watershed modeling (Jordan, 2007; Singh and Woolhiser, 2002). *The DPSM is an ordered array of numbers representing spatially distributed net power capacity* (Figure 4). Net power capacity (NPC) is defined here as the power production potential (P_{PP}) of the cell minus the power demand (P_D) of the cell and is the value in each raster cell of the DPSM. The array of NPC values populating the DPSM creates a scalar-field, which is also a geometric surface (Jordan, 2007). P_{PP} is determined from energy potential mapping processes for available energy resources, which are then combined and de-conflicted. The combination and de-confliction procedure must also consider local preferences and land-uses and not solely optimization or power production. P_D is merely the power demand requested by the user(s) in the cell. Power is the preferred unit, and so the DPSM represents an instant of P_{PP} and P_D, as opposed to an averaged net energy profile.

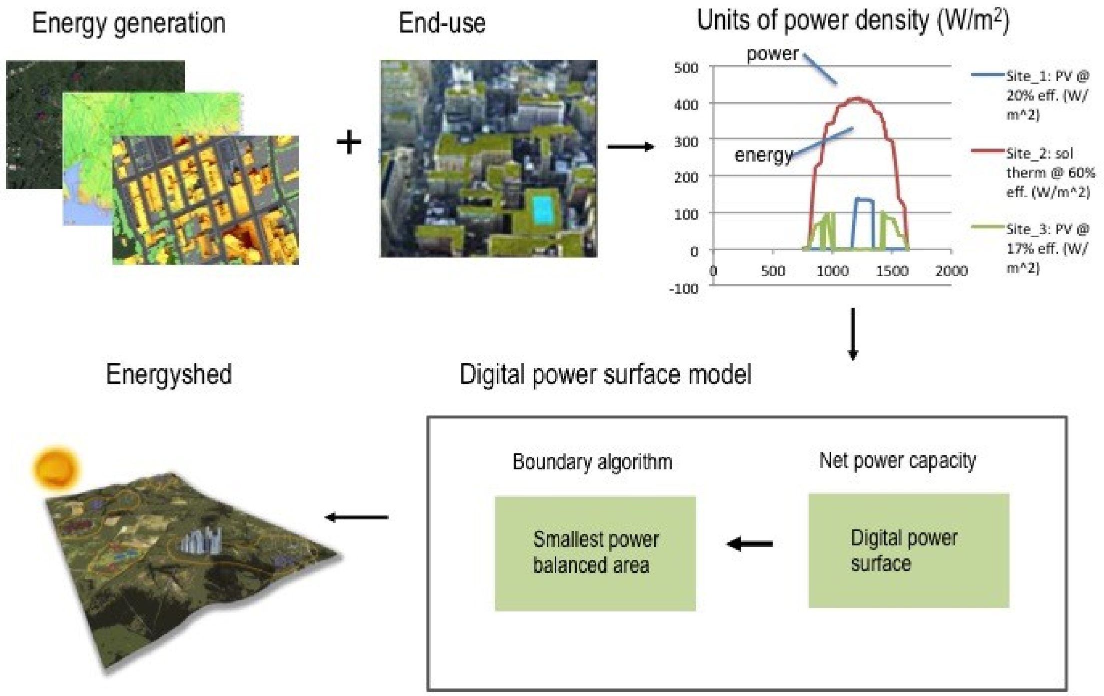

Figure 4. Digital power surface model

6.5.2 Characterizing the energyshed from the DPSM

The continuous geometric surface of the DPSM represents a basic energy terrain with units of power density or W/m^2. Other features, known as primary attributes, can be derived directly from a DTM, to include: elevation (magnitude), slope, aspect, flow path and path-length, upslope area, and fractal dimension (Jordan 2007; Bolstad, 2008); all have readily apparent utility in describing the similar or analogous features of the energyshed. The combination of primary attributes produces secondary, or compound, attributes to describe a process occurring on the terrain, such as erosion (Jordan, 2007). Topology is "the relative location of geographic phenomena independent of their exact position" (de Smith et al., 2009, p41). The topological properties of dimensionality, adjacency, connectivity, and containment (de Smith et al., 2009) can also be developed from the DPSM for characterizing the energyshed and its components.

The energyshed is determined by seeking the *smallest area of power balance* in which the sum of all NPC is zero (Equation (1)). Secondarily the shortest total path-length required for power distribution is sought so that transmission losses and infrastructure are minimized. A minimum spanning tree produces optimum path routing from end-use demand, sites with negative NPC, to nearby production sites with positive NPC (de Smith et al., 2009). The energyshed can then be considered as the smallest contiguous land extent to which energy users must connect to fulfill their energy requirements.

Equation (1): $\sum_{i=1}^{j} NPC = 0$ where j is the total number of cells in the energyshed

A few technical points are worth noting. First, the discussion of the DPSM is primarily intended for electrical power, since the stable trend is toward electrification of power, although the principles could also be used for other renewable sources such as biofuels (Edmonds et al., 2006; Smil, 2008). Second, when creating a DPSM I recommend using the same reference system and a compatible cell size, typically around 20 m x 20 m, with existing DEM-based models such as used for energy potential mapping, land-use planning, and watershed delineation, to make downstream integration more accurate. The energyshed is a nested construct. A net-zero building with a zero NPC is technically its own energyshed, and although this is of some interest for the characteristics of a larger, municipal-sized energyshed, the calculation can be extended outward for the next successive energyshed(s) in the nested hierarchy. Choosing a reasonable reference point from which to start the energy balance will enhance the meaning of the result. The local urban center is a good initial option, or the "center of mass" of a local representative area of demand in an area of interest.

6.5.3 Representing time in the energyshed

DPSMs constructed for limiting conditions of NPC will generate the limiting extents of the energyshed: minimum extent for the most optimistic production and minimum demand; and, maximum extents for the most pessimistic production and robust demand. GIS currently has limited options for portraying change through time, the primary being a series of maps representing conditions in different times (de Smith et al., 2009). Application of agent-based modeling techniques to GIS holds promise and potentially substituting the scalar value of NPC with a time-domain equation of NPC may facilitate temporal behavior modeling (de Smith et al., 2009). Computing capacity and knowledge of the temporal behaviors of both renewable energy production and end-use in the cells would be required, albeit the temporal behaviors of generation and end-use are ultimately stochastic. Nonetheless, it is not difficult to conceive of a distributed smart grid that would have nearly instantaneous generation and demand information available to dispersed users and producers throughout the grid. For now, the snapshot method will suffice to identify energyshed extents under limiting scenarios.

CHAPTER 7. CONCEPTUAL AND PRACTICAL IMPLICATIONS: ENERGYSHED STRUCTURE

"The basic problems in modern physics are problems of organization"
Ludwig von Bertalanffy (1950, p.134)

A system is a "complex of interacting elements" (Bertalanffy, 1950, p143). System structure determines system behaviors (Sterman, 2000; Meadows, 2008). The intent of this chapter is to explore the structure of the proposed system of the energyshed to identify important relationships therein and to provide additional description of the energyshed and potential behaviors. I will discuss this primarily in the language of system dynamics, the field of study attuned to identifying system structure from observed behaviors. In this discussion observed behaviors are replaced with desired behaviors to facilitate identification of the required structure to create behaviors consistent with a coherent, efficient, inclusive and healthy energyshed. These behaviors must also combine to meet the purpose of the energyshed to: *provide the functions and structure to harvest and dissipate energy to support life, activity, and productivity throughout the energyshed without polluting the environment above its capacity to assimilate those pollutants.* Dynamical systems work well because they exhibit hierarchy, resilience, and self-organization, which are attributes emerging from structure (Meadows, 2008).

Structure simply refers to "The arrangement of and relations between the parts or elements of something complex" (Structure [Def.], n.d.). On identifying structures and processes, Ahl and Allen (1996) propose that recurring and stable configurations in experience identify the system as its own entity. Fisher (2010) considers structure as " pattern or observable uniformity in terms of action or operation taking place" (p.77). In the field of system dynamics, system structure is described by the feedbacks loops, stocks and flows, and nonlinearities produced from that structure and the decisions of the agents operating within the structure (Sterman, 2000). The system structure and thus its behavior can be described by a small handful of system modes, e.g. exponential growth governed by reinforcing feedbacks, or goal-seeking governed by balancing feedbacks (Sterman, 2000).

7.1 Component function

The behavior of the components in context of the energyshed and to each other is an origin of system behavior (Sterman, 2000; Meadows, 2008). Each of the eight components conducts an essential role, or function, to support the achievement of the purpose of the energyshed to harvest and dissipate energy (Table 5). Function refers to the natural activity, purpose in design, or operation of a unit in terms of its contextual structure (Function [Def.], n.d.; Fisher, 2010). The interactions, or feedbacks, of the components, rather than the complexity inherent in the components, produce the complex behaviors of the energyshed (Sterman, 2000). The distribution component provides a good example of the complexity formed by component interactions. The distribution system determines which other elements of the energyshed components are connected and thus where energy might be channeled, affecting end-use, storage, and consequently information. A change in type of distribution would promote or eliminate some energy carriers preferentially over others. Connection changes to storage would alter the buffering capacity of the energyshed potentially causing wild oscillations of energyshed area and stability.

Purpose and function are often used interchangeably; purpose is often attributed to a human and function to a thing (Meadows, 2008). Purpose will refer here to the behaviors from the perspective of the system as a whole, while function will refer to a downward view of the behaviors of the subunits in context of the surrounding system. Meadows (2008) suggests that components may develop purposes that do not match intended function and can produce unwanted behavior. Each energyshed component is itself a holon, exhibiting an affinity for both organizational inclusion and self-assertion (Koestler, 1970). Component motivators, such as ownership structures, must be considered carefully for practical energyshed design, should support the values presented in chapter 4, and also harness the benefits of strong self-organization processes.

Table 5. Energyshed component function

Component	**Primary function:**
Energy resource	Provides power flow into the energyshed
Generation	Transforms a fraction of the available energy resource into an energy carrier
Distribution	Connects system components; channels the energy carrier
Energy carriers	Transfers power in useful form
Storage	Stores energy carriers; buffers system
End-use	Dissipates power for work
Waste heat and entropy	Rejects unusable energy; maintains accounting for laws of thermodynamics
Information	Produces (from internal processes) and disseminates signals for feedbacks, facilitating control/learning/adaptation/evolution; bounds and channels information signal

7.2 Process

Processes produce change within the system, and can affect system behavior through time. A process is "a natural series of changes" and also refers to the series of actions taken to achieve that change (Process [Def.], n.d.). Losee (1997) contends that processes are similar to mathematical functions with inputs placed through an algorithm that return a single value, and "every process may be defined functionally and may be defined by one or more functions" (p.258). The process is a precursor for information development (Losee,1997) and thus an originator of information in Shannon's (1948) information system construct. As a process changes the state or configuration of a system, the values associated with the outcome of the process are the feedbacks to the system (Sterman, 2000). Feedbacks directly control system stability and so a process as an originator of feedback can then greatly affect system stability.

Erosion is an example of a geomorphological process that occurs in context of the watershed (Leopold et al., 1995). As erosion occurs elevation is lost in the eroded area and more runoff is potentially channeled through that stream and with greater velocity, removing more material (Rodríguez-Iturbe and Rinaldo, 1997). This is a reinforcing feedback. Conversely, as stream flow is reduced, deposition occurs, potentially slowing stream flow further; this is another reinforcing feedback (Leopold et al., 1995). Under some conditions stream capture may occur and the flow of one stream can become pirated by another (Rodríguez-Iturbe and Rinaldo, 1997). The rapid reinforcing feedback causes the local stream network to radically change contributing area, location, and even basin boundary (Rodríguez-Iturbe and Rinaldo, 1997). Erosion is an example of a self-organized process driven by the release of energy from the changing configuration of the elevation of the water in the context of the gravitational field. The work is accomplished through water and sediment transport.

7.2.1 Geomorphology of energy systems

Work is the useful form of energy that produces transformation to include dislocation and deformation of materials across the land surface. This occurs for instance within the production-side of the energy industry for mining of resources, the transportation of those resources, or the installation of infrastructure. The combined land footprint attributed to the energy chain of the current energy system, as of early 2000, in temperature climates is estimated at approximately 10% of the equivalent area of impervious-surfaces for low-per-capita-energy-use societies and up to 20% for high-per-capita-energy-use societies (Smil, 2008). Energy is not just linked to expansive landscape changes from its production but the dissipation of energy is required as the motive force behind the transformative processes in every other endeavor. Geomorphological change, through erosion for example, is a function of energy dissipation within the context of the watershed

(Rodríguez-Iturbe and Rinaldo, 1997), so too geomorphological change in general is a function of energy dissipation. These landscape transformations are inter-related from an energy system perspective in that each land-use modification affects the set of feasible alternatives available on a site for energy utilization. When considering this in terms of a local energy balance, the benefits and consequences of the energy system are more closely co-located and felt acutely through the transformation of the local landscape.

7.2.2 Processes of the energyshed

The "natural series of changes" that occur in the energyhed is the restructuring of the land surface by the development or removal of energy infrastructure and the consequent alteration, disruptive and enhancing, of land-use caused by the energy infrastructure (adapted from Process [Def.], n.d).

"The character of the landscape is shaped by the interaction of biophysical processes and human problem solving. It is in the framework of this relationship that landscape sustainability must be addressed" (Allen, Tainter, and Hoekstra, 2003, p201). Land is a limited commodity and many critical land-uses are partially or mutually exclusive and land-use at one site can produce effects, such as hydrological and climatic, at both nearby and distant sites (Seto et al., 2010). The various natural and anthropogenic landscapes and the biota and infrastructure on them have varying capacity to capture and convert incoming solar radiation into usable products and services (Jørgensen, 1999). Gross primary productivity (GPP), net primary productivity (NPP), and human appropriated net primary productivity (HANPP) are the metrics of ecosystem goods and services balance in context of human economy (Seto et al., 2010; Haberl, 1997; Haberl, et al., 2007). Primary productivity refers specifically to phytomass production from captured photosynthesis as a proxy measure for ecosystem health as compared to both positive and negative human impingement on phytomass production capacity (Haberl et al., 2007).

The energyshed can be conceived as a set of smaller land areas, which I will call sites, and then there can be sub-sites and so on across meaningful levels of spatial scale. I am choosing to differentiate site from cells to gain freedom from the relics of the raster-grid for this discussion and to permit more focus on the coherence of the land-based processes within the energyshed, but rasters will likely be the data model of choice for modeling the processes across the energyshed. Each site has some amount of energy flow through it from the sun, wind, or other resources (Figure 5). The site has some capacity to utilize that energy flow. A desert landscape might utilize 2% of the exergy available in incoming solar radiation, a lawn slightly more, and rejects the remainder through reflection and heat. Alternatively, a matured deciduous forest utilizes 70- 80% of that incoming solar exergy for GPP and any ecosystem goods and services associated therewith (Jørgensen, 1999; Allen et al, 2003). An agent or a community might decide to install PV panels on the site. If the forested site was completely covered by PV system then that 70-80% utilization of solar energy by the flora and fauna on site would no longer be available for GPP, but transformed, to a form that prevents any other utilization of the solar energy on that site. The solar panels could convert up to 15-20% of the solar that impinged upon the solar cells in the PV panel, and the cost would be effectively all of the incoming solar energy flow at the site and may also prevent harvesting other flows, such as wind. The site now contains the PV system, and no longer contains the deciduous forest infrastructure (biomass), which also functioned to provide transpiration in the hydrological cycle. The PV system requires a different form of energy for maintenance, human and electric power for instance, than did the deciduous forest which subsisted directly from the flow of solar radiation.

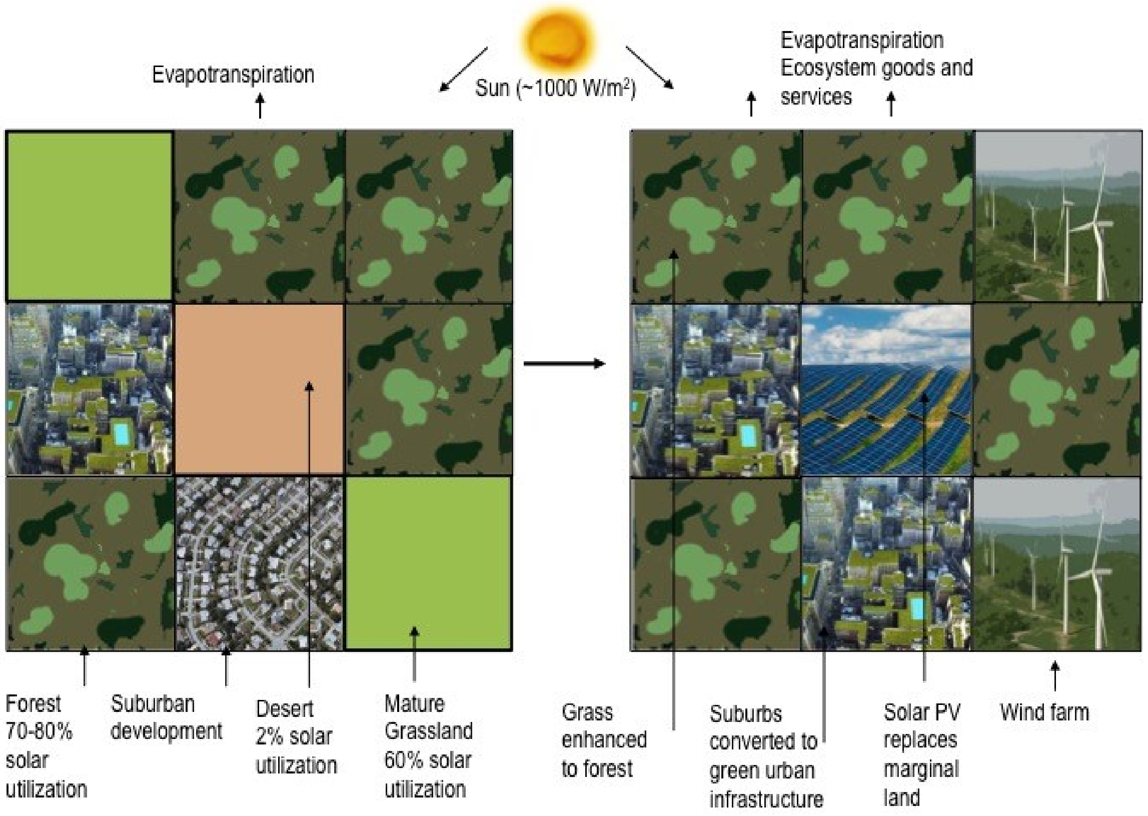

Figure 5. Energyshed geomorphology

From a process standpoint on the site, energy system generation infrastructure is now present on the site, while biotic energy infrastructure in the form of phytomass has decreased, or been removed from the site. In terms of primary productivity, HANPP has increased and GPP and NPP have both decreased, affecting energy utilization and potentially overall health of the energyshed. The site has undergone a transformation that affects the energyshed as a whole, and of course was enabled by dissipation of energy. Energy generation and primary productivity both represent useful and required infrastructure within the energyshed. Although primary productivity is a very useful accounting tool, in terms of the energyshed, the balance of energy as it ebbs and flows must be considered at the site and across the energyshed to develop possibilities and constraints to what might be accomplished with that energy flow.

Accounting directly for energy is more inclusive than accounting for primary productivity in that it admits a more complete set of energy utilization, not just photosynthetic, and is not necessarily more complicated than GPP calculations. The ratio of energy utilized to energy flow available can perform as a metric of the *productive development* of a site(s) and also for the energyshed as a whole. Areas of low productive development and higher technical production potential would be candidates for energy infrastructure or ecosystem enhancement depending on the most pressing need. Remote sensing technologies and GIS have the capacity to populate an energyshed model with meaningful data and information (De Smith et al., 2009; Bolstad, 2008). Energy balance can be accomplished at finer temporal resolution than primary productivity, which requires time for biomass production.

7.3 Mode, relationships, and self-organization

7.3.1 Mode of behavior

The energyshed has a goal, its purpose, to produce the power consumed within it. Consistent with other biological dissipative systems (Martyushev, 2013), it is expected that in the energyshed the tendency will be to maximize dissipation of the available energy gradient until constraints are encountered. The history of both coal and oil support the human tendency for increasing dissipation of available energy (Rutter and Keirstead, 2012). At the heart of the energyshed system behavior, in its simplest form, the system will seek its goal with growth tempered by a balancing feedback produced primarily through land-use conflict, although the primary feedback may vary with location and specific conditions (Sterman, 2000; Meadows, 2008). Other significant constraints in a practical system would include the energetic, monetary, maintenance, and ecosystem burden associated with energy end-use and thus generation, distribution, and storage of energy. These forces will tend to expand the energyshed toward available and less expensive land, away from the more heavily populated demand-centers in the city, and thus reduce generation density until constraint is encountered. External forces, such as political boundaries, land access, and the unnecessary cost of transmission, for instance, will act to compress the energyshed and thus densify generation. The combined effect of these forces may impact demand, altering end-use. Ideally, each energy community can find its balance, preference, and self-sufficiency.

7.3.2 Topology

The criteria for boundary determination are central motivations to the application of a shed construct to an energy system. Boundary defines the extents of analysis and containment of elements. Without a boundary the system eludes clear definition or analysis. The energyshed, the watershed, and the airshed employ a contiguous boundary containing the entire process, which is not explicitly so with the foodshed nor the fossil-fuel energy system, for which supply and demand are generally separated and require transport (USEPA, 2015; Schumm, 1977; USEPA, 2014; Peters et al., 2009). In the energyshed all components are explicitly contained within the energyshed, making an energyshed self-sustaining and complete. The boundary oscillates between limiting cases of generation and end-use that requires larger and smaller land areas for power balance, within context of the tendency to maintain the energyshed as small as reasonably possible. Storage capacity buffers and stabilizes the boundary oscillations. In a practical system some engineering will most likely be required to stabilize the boundary at an acceptable location for the community and local management. Conceptually, the boundary inherent in the definition and the edges should provide an interesting point of analysis, as sheds interact with one another and elements shift into and out of adjacent energysheds. The edge may have its own functionality.

Adjacency and proximity are important determinants for the components in an energy system. Transmission losses, infrastructure burden, loss of coherence and control in the system, dislocation of benefit and impacts, and the unnecessary burden of middlemen along what can be circuitous routes from securing the resource to end-use, are costs associated with non-adjacency and distant proximity (USDOE, 2002; Volk, 2013; Willis, 2004). An off-the-grid building represents an extreme case of an energyshed in which all necessary parts are adjacent to include generation, storage, and end-use; distribution is not required. The calculus of trade-offs among power availability, storage capacity, and distribution for energy averaging with proximate neighbors, would need to be weighed for the circumstance. Regardless, even if partial load was supplied by adjacent generation, the distribution component used for energy averaging and balance would benefit from smaller infrastructure and reduction in amount of equipment such as step-up/step-down transformers. In situations requiring longer distance transmission, the cost burden of infrastructure could be subsidized by those directly using the service; this fee structure would advantage the development of local generation infrastructure.

7.3.3 Connectivity

Connectivity governs how matter, energy, and information are exchanged between system components and is a key property in high throughput dissipative systems such as ecological, hydrological and geomorphic systems (Phillips, Schwangart, and Heckman, 2015). Connectivity is a measure of the connectedness of the nodes and may be uni-, bi-, or multi-directional (Phillips et al., 2015). A basic example is the distribution system that connects the components of the energyshed and sub-networks that connect the elements within the components. Nodes can have higher or lower quality of connection, affecting structure (Phillips et al., 2015). Connectivity also has emergent properties such as percolation, which would represent physical connection across the energyshed (Falconer, 2014). Phillips et al. (2015) notes that graph theory has the capacity to identify, explore and/ quantify the following properties that are relevant to analysis of an energyshed: spatial relationships, types of structures and implications for behavior, scale-free properties, dynamics, connectivity, centrality, clustering, complexity, coherence, stability, synchronization, and vulnerability. In ecology, landscape connectivity is defined as "the degree to which the landscape facilitates or impedes movement among resource patches" (Taylor, Fahrig, Henein, and Merriam, 1993, p.571). Analogously, *energy connectivity is the degree to which the energy transfer between components is facilitated or impeded.* This definition can also include energy-related information required for feedback.

7.4 Fractals: indicators and limiting ideals

Fractals are inherently very efficient forms, particularly for their ability to fill space with maximum connectivity and least path length (Rodríguez-Iturbe and Rinaldo, 1997). Perhaps because they are such efficient forms, fractals are ubiquitous in nature (Mandelbrot, 1983). Mandelbrot (1983) first coined the term fractal and formally defined a fractal as a set for which the fractal dimension, more formally known as the Hausdorff-Besicovitch, is greater than the topological dimension. The dimension of the structure is often non-integer or fractional and so the source of the term, *fractal* (Mandelbrot, 1983). The fractal exhibits self-similarity, and potentially self-affinity, through multiple levels of its organizational hierarchy, indicating similar and recursive mechanisms at work (Ahl and Allen, 1996; Falconer, 2014). The equation form $f(x) = cx^{\beta}$ is a power-law characteristic of fractals. On a log-log plot the scaling exponent, β, is the slope of the line and the fractal dimension (Falconer, 2014). Fractals are the fingerprint of self-organized criticality (Bak, Tang, and Wiesenfeld, 1987). Self-organized criticality is the fingerprint of energy dissipation (Nicolis and Prigogine, 1977; Tang and Bak, 1988). Self-organizing behavior represents "optimal organization that ensures maximal capacity at a minimal cost" (Laurienti et al., 2011, p.3610). Energy dissipation, self-organized criticality, and fractals often appear together in biological and social systems and, since the triumvirate are outcomes of non-equilibrium thermodynamic process, are the underlying dynamics of many natural processes (Mandelbrot, 1983; Bak 1996; Bak and Paczuski, 1995; Nicolis and Prigogine, 1977; Sneppen, Bak, Flyvbjerg, and Jensen, 1995).

Energy systems are directly concerned with energy dissipation and so barring any other interfering structuring processes, an efficient energy system at its barest would have fractal and self-organizing characteristics. Fractals do appear regularly in energy and related systems. Energy distribution systems, such as electrical transmission and distribution, or natural gas distribution, exhibit fractal characteristics in their dendritic structure, which is consistent with their purpose to most efficiently connect users within the service area (Laurienti et al.,2011; Scott and Willis, 2000). Hunter-gatherer range area for energy-resource gathering scales fractally with population; this is consistent with the range behavior of social animals in general (Hamilton et al., 2007). Cities, as energy dissipaters with large throughputs of energy, are governed by energy metabolism for their associated connectivity networks, growth dynamics, and transportation systems (Batty, 2010; Sante Fe Institute, 2015; Decker, Kerkhoff, and Moses, 2007; Salat and Bourdic, 2011; Khan, 2014). City size seems to follow a lognormal distribution for smaller cities indicating probabilistic mechanisms but approaches power-law distribution for larger cities indicating multiplicative or recursive mechanisms (Decker et al., 2007). Power-law scaling in city structure indicates a more efficient use of energy (Salat and Bourdic, 2011; Bristow and Kennedy, 2013). Fractals also appear in information signals and in social systems such as markets, which are dissipative systems (Mandelbrot, 1983; Annila and Salthe, 2009).

Although there is a growing body of work on fractal scaling and self-organization of energy dissipating systems, the exploration of energy systems themselves, as opposed to the effects of energy systems such as markets or urban infrastructure for instance, as self-organized and fractal is in its infancy. The importance of such work lay ahead with transition to renewables-based energy systems, for changing the energy resource changes the phase space of the system and thus is expected to significantly alter system behavior (Allen et al., 2003; Kerkhoff and Enquist, 2007). The application of fractals to energy systems and the energyshed has many potential uses:

- Measure of distribution structure and efficiency (Laurienti et al., 2011; Batty, 2010)
- Measure of efficiency of energetic harvest from land area as compared to population (Hamilton et al., 2007)
- Measure of size distribution of components and elements within the energyshed and energysheds across a region (Decker, Kerkhoff, and Moses 2007; Salat and Bourdic, 2011; Kerkhoff and Enquist, 2007; Batty, 2010; Smil, 2008; Grubler, 2012)
- Scaling to inform interventions for system resilience (Kerkhoff and Enquist, 2007)
- Scaling laws to define the constraints of state available to an ecosystem, narrowing the phase space (Kerkhoff and Enquist, 2007)
- Scaling laws to identify an "ideal", or limiting, steady state. Understanding divergence (non-steady state) from the scaling law can identify disturbances, other structuring processes involved, and when a system flips to a new state (Kerkhoff and Enquist, 2007)
- Scaling law applied to policy to inform performance indicators and target development.
- The specific parameters of the scaling laws serve as a characteristic fingerprint of an energyshed in its specific circumstance and for comparison between energysheds

Calder (2000) (in Kerkoff and Enquist 2000, p493) suggests applying scaling laws to derive surrogate laws in face of uncertainty as a tool for adaptive management. The recommended process is to derive scaling relationships from empirical data; predict the relationships; and, fine-tune the predictions based upon departures from the scaling relationships (Calder, 2000; Kerkhoff and Enquist, 2007). Because fractals are the resulting structures of energy dissipation processes, structures within an energyshed will exhibit fractal properties. The proximity to fractal form will indicate efficiency in form whereas a divergence may indicate the presence of other strong structuring mechanisms taking place within the energyshed. Fractal scaling characteristics can be compared across energysheds and patterns may emerge among energysheds in similar environmental circumstance, geography, and demographic or may be more universal. Either way applying fractal analysis to an energyshed and across energysheds will conceivably provide insightful characterization of the structures and processes occurring within.

CHAPTER 8. CONCLUSION

The energyshed conceptual framework was developed to present a coherent organization for renewable energy systems at a local level that permits exploration of important interconnections with other vital ecosystem elements, is accessible to local planning processes, and is not bound by the inertia of fossil-fuel paradigms. In this monograph, I presented the conceptual basis for the construct of the energyshed. The research has also uncovered a set of conclusions suitable as recommendations applicable not only to the development of an energyshed but also appropriate for application to community energy plan development and operations.

8.1 Key conclusions

Employment of renewables should be prioritized over fossil fuel efficiency

Technical potential capacity of solar-based energy is not limiting; the existential threat of anthropogenic climate change is limiting. Early-stage ecosystems (renewable energy) rapidly build energy dissipating structures while matured ecosystems (fossil-fuel energy) nearing constraint focus more energy into efficiency. Mature ecosystems still seek maximum energy dissipation and so do not tend to use less energy. Efficiency measures for carbon technologies only perpetuate the damaging system, while instead these efforts could be redirected toward harnessing the underutilized solar energy gradient.

Reliance on the energy transmission system should be curtailed

In a locally-energy-balanced system, the transmission system becomes unnecessary. The North American transmission system is a complex, aging and brittle system. The system is stressed by loading, lagging investment, market liberalization, power losses in the system, and penetration of RETs onto the grid. Upgrade cost offsets can be directed into RET deployment and local distribution system upgrades. Pay-per-use of the transmission grid would provide financial incentive to motivate energy trade and increase RET employment within the energyshed area as opposed to distributing the substantial cost of the transmission system over all users.

Cities as an important nexus for sustainability should be the focal point of renewable energy system organization

Cities have unique capabilities to shape the energy system and so are primary leverage points. Most energy end-use occurs in the urban environment and, within the OECD, most capital expenditure occurs at the end-use side. End-use and supply technologies co-evolve, indicating a strong role for bottom-up energy system transition. Additionally, cities perform many roles that can directly or indirectly alter the nature of the energy system in the locale, in particular the setting of land-use bylaws and information flows.

Coherence, efficiency, inclusivity, and health as a more holistic value set for renewable energy should supplant energy security

Energy security is an oil-myopic value referring to maintaining the flow of oil to OECD countries. I recommend that ecosystem-based values of a coherent, efficient, inclusive, and healthy energy system supplant energy security to re-align focus into the energy transition and not perpetuate a backwards-looking value.

Information surfaces should be re-aligned to facilitate the energy commons

Adequate energy information does not currently flow across the energy commons. Energy generation and consumption directly impact the commons and so all relevant data, and the ability to generate data, from generation to end-use will need to be transferred to the public realm to operate an inclusive energy system. This information can then be used for evidence-based decision-making, and improvement in the quality of energy-related decisions at all levels of organization. The smart-grid is the emerging tool of information flow within an energy system; with properly aligned purpose and surfaces, the smart grid is a promising technology for connecting the energy commons and enabling the energyshed.

Renewable energy system should be placed back into the commons

A healthy ecosystem, one with vigor, diversity and resilience, requires inclusion. Share information, reacquire the local distribution infrastructure, encourage local energy trading, and develop management processes to support local energy balancing. Move the energy system back into the public realm and stop atmospheric GHG pollution when there are other viable options.

Renewable energy should be organized around its fundamental land unit

Because of their low power density, RET is land-area-intensive, which when considered with other land-use requirements is likely to be the constraint for RET generation in most circumstances. Considering renewable energy from the perspective of the fundamental land unit of energy, the energyshed links energy to land as the integrative commodity. This is appropriate since the energy system can be described spatially as can its process of land transformation, and facilitates integrative planning with other critical land-uses. The benefits include accessing a coherent conceptual, analytical and practical energy system model applicable across multiple useful size levels of scale. Refocusing the organizing principles of energy to land and the physical processes of energy production provides new conceptual space to shake free some of the existing paradigms associated with energy that follow political, economic, and social structures and habitual patterns that are less useful and in cases socially and environmentally damaging.

Digital power surface models should be developed to determine local energy balances and energyshed boundaries

Energy cartography is capable of producing high-resolution models of renewable energy production potential across city-size areas. Power is a better metric to accommodate the intermittency of renewable energy. The DPSM is proposed as a power surface model for determining local power balance for a set of given initial conditions. More-advanced treatment would include agent behavior modeling to estimate the shifting nature of the power balances within the energyshed and consequently the boundary. Energy cartography is a promising discipline for advancing renewable energy planning, but more work in the field is needed to consolidate current techniques and then to integrate generation, end-use, and various RETs.

Fractal analysis should be applied to determine some of the performance indicators and targets for the energy system

Energy dissipation, self-organized criticality, and fractals are fingerprints of energy dissipation systems. As a reflection of energy dissipation, urban development tends to demonstrate fractal patterns in some parameters. Fractal characterization of the energy system and the energyshed can be applied as a limiting performance ideal and indicators and targets for management.

8.2 Research Agenda

The energyshed framework creates opportunity for a robust new research agenda for the study of renewable energy system organization, function, and behavior through the panorama of the fundamental land unit and emerging interactions from the growth of employed RET. Initial research could focus on energyshed: (1)

information flows, (2) modeling and behaviors, (3) technology, and (4) methods of practical implementation.

(1) Modeling is an important next step for the energyshed to understand its behaviors and characteristics for adaptive management, control technologies development, and general evolution of human-deployed energy systems. The energy mapping community could benefit from better consolidation and from that consolidation can further advance mapping techniques to explore power-based, as opposed to energy-based, analysis over a contiguous area that is then modeled across a period of time. This will bring the tools of energy engineering and those of wide-area renewable planning closer together.

(2) In parallel, current information flows concerning the production and use of energy must be re-aligned, particularly at local levels, and placed into the public purview as is the pollution produced by fossil-fuel combustion. Detailed analysis of local energy production potential and consumption patterns is needed to refine understanding of the behaviors and characteristics of each energyshed. The local results can then be compared with other energysheds for trends and baselines.

(3) The energyshed construct extends a challenge to consider and develop smart grid technology to support a bottom-up, self-organized, locally-based energy grid suitable for freely flowing local energy exchange. This is fundamentally different than a top-down-control design for centralized generation and demand-side management. Both modeling and technology development supporting this alternate view of the smart grid are available avenues for scientific pursuit.

(4) As energysheds are modeled and developed, practical system characterization compared to each other and fractal ideals, such as area relationships, distribution forms, and percolation, can create baselines and permit identification of anomalies and substantial divergence from ideal baselines. Topologic and fractal pattern analysis applied to the study of the dynamics and energy–driven geo-morphologic processes in the energyshed is an important near-term step in building an understanding of the benefits and potential impacts of the energyshed form for energy organization. Finally, the practical application of the

framework itself by a community will require thoughtful experimentation, supporting analysis, and codification of learning produced in execution.

The energyshed provides a holistic framework for comparing and sharing best practices for energyshed planning, development, and operations. The energyshed framework opens the door to an uncharted field of energy planning, land-based RET analysis, and integrated impact assessment with other land-based critical resource systems.

8.3 Implementation strategy: *On Averting the Tragedy of the Commons*

In "On Averting the Tragedy of the Commons", de Young and Kaplan (1988) offer a tripartite framework for environmental policy development for wicked environmental problems: exploration, stability, and distributed leadership. Exploration of potential solutions at a small scale mitigates whole-system risk and permits parallel explorations to occur simultaneously, thus improving synergy and compressing the time to find adequate solutions (de Young and Kaplan, 1988, p.277). A stable support structure provides "continuing and reliable support", is a vetting ground for alternatives, mitigates risk for those conducting the explorative experiments, and frees them from having to prepare for all possible contingencies, encouraging participation and expediting experimentation (de Young and Kaplan, 1988, p.277). Distributed local leadership inspires and engages a diverse set of contributions, skills, abilities and interests, expanding possibilities and fostering ownership (de Young and Kaplan, 1988, p.277). Leadership from local actors was the model for successful experimentation and subsequent implementation of: automobile emissions standards, low-emissions-vehicles programs, recycling, consumer warning programs for harmful substances, land transfers, and municipal solid waste programs (Brown and Sovacool, 2011).

The energyshed conceptual framework is ready for adoption and application in cities seeking to transform their energy systems for a socially and environmentally healthy future. The design principles and recommendations can be applied both in full for a rapid run toward a self-reliant and resilient energy system, or in part for a more gradual transition depending upon the political will and capacities of the locale.

The impacts of immediate change will provide much greater benefit and so while research seeks the most refined solutions, we must move forward with the child's mind, implementing and learning, but not fearing to try. Transition from fossil fuels to renewable energy is a wicked problem (Brown, Harris, and Russell, 2010) and requires expedient solutions. The next step toward the implementation of local renewable energy organization is to enlist several participant cites, villages, and/or municipalities supported by regional and national government, research and industry to explore their unique energyshed structure and to identify successes and challenges to implementation. The risks are low and the potential payback is great. The most critical moment for creating success is in seeing and not ignoring the great opportunity as it presents before us, even if it is disguised as a wicked problem. Can we consciously and rapidly create a coherent, efficient, inclusive, and healthy energy system? The answer to this question remains to be lived, but anthropogenic climate change poses a great impetus to try. The energyshed would expedite appropriate interventions.

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