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Evaluating microgrid effectiveness in transitioning energy portfolios

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EVALUATING MICROGRID EFFECTIVENESS IN TRANSITIONING ENERGY PORTFOLIOS

by

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ABSTRACT

Microgrid energy systems have emerged as a potential solution to rising greenhouse gas emissions from dependence on fossil fuels. This research provides a framework for evaluating the utility of microgrids. Three key findings are presented: use of a state-of-the-art matrix (SAM) analysis to identify gaps in key research areas that inhibit wide-spread microgrid adoption, development of a system dynamics (SD) model, and a cost benefit analysis case study to evaluate microgrid feasibility in partially meeting the energy demand of a building. Governments play a central role in developing clean energy strategies. A SAM was developed to determine if key microgrid barriers to adoption defined by a state government were being addressed. The results of the study suggest that environmental and sustainability benefits had not been sufficiently addressed. Using the SAM findings, an SD model was used to evaluate the environmental and sustainability benefits of transitioning a state's residential electricity portfolio. The SD model outputs suggest that fossil fuel depletion and greenhouse gas emissions would be reduced, but the financial investment would be significant. Lastly, a cost benefit analysis was conducted on a microgrid partially meeting the energy demand of a university campus building. The results demonstrated that selection of a proper discount factor and recognition of useful life are critical success factors for microgrid energy projects. Collectively, these findings provide the engineering manager with a method to evaluate the feasibility of proposed microgrid projects, the city planner with the system-level implications of a large-scale energy transition project, and the policy maker with the necessary information to develop policies that promote a clean energy future.

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1. INTRODUCTION

The environmental impact of human behavior has been so severe that it has resulted in a new epoch on the geologic time scale, the Anthropocene. The term was coined by Nobel laureate Paul Crutzen in 2000 and has appeared in hundreds of peer-reviewed journal articles since the International Union of Geological Scientists (IUGS) declared the new epoch in a 34-1 vote in 2016 (Angus, 2016). In so naming the present a new epoch, the IUGS gave further credence to the concept that humans are responsible for global climate change.

One of the primary drivers of the new epoch is the release of carbon into the atmosphere. The Mauna Loa Observatory has kept a record of atmospheric concentrations since 1960. A graphical representation of their findings can be found in Figure 1.1.

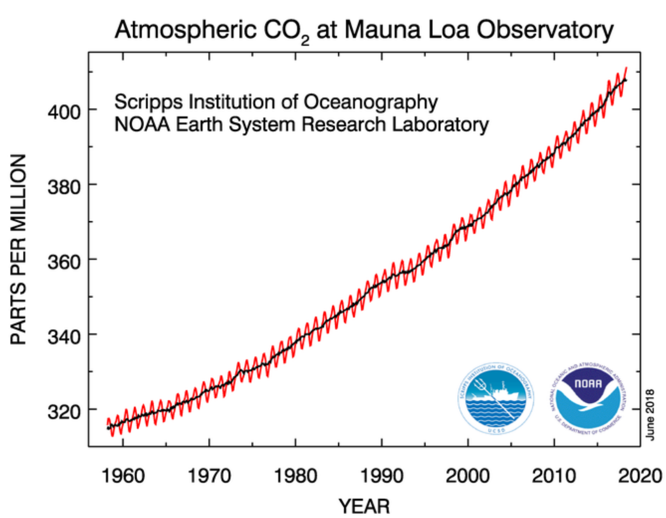

Figure 1.1. Mauna Loa Observatory Data (NOAA, 2018)

There are two distinct curves in the figure. The red curve measures carbon dioxide as a mole fraction in dry air while the black curve presents the seasonally corrected data. As the figure suggests, the concentration of carbon dioxide in the atmosphere has risen from approximately 320 parts per million (ppm) to greater than 400 ppm. The difference between these two values may seem insignificant or even baseless. To better understand the impact such an increase has had on the environment, a brief survey of the consequences regularly attributed to global climate change is required. The impact global climate change is expected to have on the environment is a dynamic discussion that is dependent on geographical location. Instead of delving ever deeper into the myriad of possibilities, the consequences of which there is much consensus are presented. NASA has conducted such a study and the results of their findings are presented here (NASA, 2014). First, global temperatures are projected to increase between 2.5 and 10 degrees Fahrenheit by 2100. As average temperatures continue to increase, the amount of arctic sea ice is expected to decrease. Each September, Arctic sea ice reaches its minimum and is declining by 13.2 percent per decade (National Snow and Ice Data Center/NASA, 2018). When ice melts it is added to the collective volume of the planet's oceans. Given more volume and expansive properties related to temperature increase, global sea levels are rising at a rate of 3.2 millimeters per year and between one and four feet by 2100 (NASA Goddard Spaceflight Center, 2018). Such a sea level rise would displace millions of people living on the coasts and devastate national economies. While the gradual increase of sea levels present a natural disaster over time, hurricanes are also expected to increase in both frequency and intensity. There is debate regarding the relationship between temperature increase and hurricanes. However, the number of Category four and five hurricanes has increased since the 1980s. The calamity caused by both Hurricane Harvey and Maria in such rapid succession give further weight to this argument. Upon reviewing the consequences of human-induced global warming, it is imperative that solutions be developed with haste. Effective solutions will target specific sectors and optimize use of their available resources. The work presented here will address energy sector. Meeting national energy demand is a complicated combination of natural resource management, infrastructure utilization, and supply chain management. Figure 1.2. illustrates the complex nature of the United States' energy infrastructure.

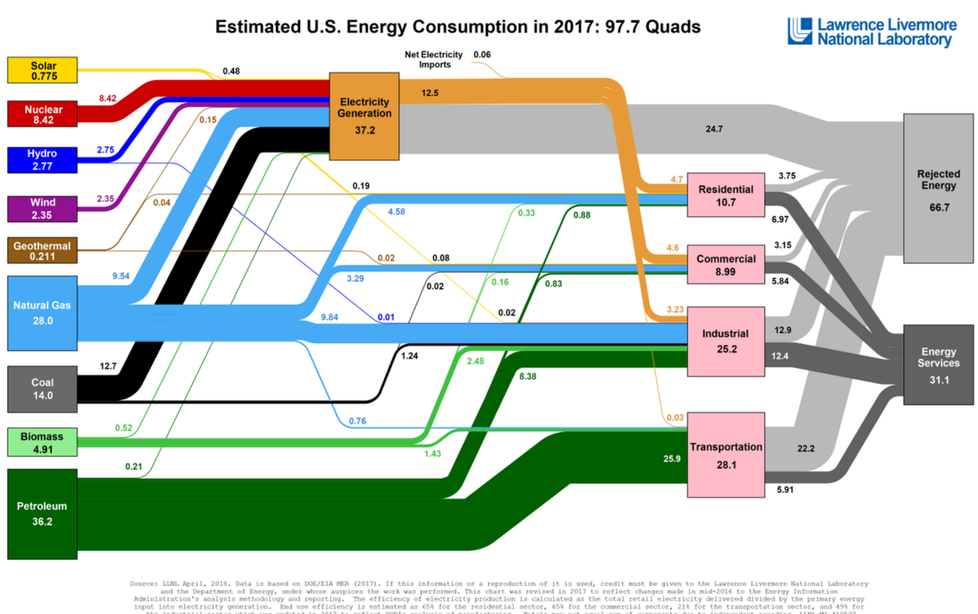

Figure 1.2. Estimated U.S. Energy Consumption in 2017
(Lawrence Livermore National Laboratory, 2017)

The figure presents two key findings relevant to this study. First, the United States is dependent on fossil fuels such as petroleum, natural gas, and coal to meet much of its energy demand. The subsequent emissions from burning these fossil fuels are a key contributor to the increase in atmospheric concentrations of carbon dioxide. Second, renewable energy technologies that only marginally affect the environment barely register in the portfolio. In reviewing the state of the US energy infrastructure, a transition towards renewable energy technologies would address the environmental degradation caused by fossil fuel dependence. Microgrid energy systems have emerged as a potential approach to transitioning energy portfolios.

A microgrid energy system is defined by the department of energy as, "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode" (DOE, 2012). As is the case with any new technology, there are barriers to adoption. The goal of this work is to address those barriers.

This work consists of three distinct papers that evaluate microgrid effectiveness in transitioning energy portfolios. The first paper is an integrative literature review to determine how effective research has been in addressing the key barriers to adoption determined by a state government. A state-of-the-art matrix is presented that clearly demonstrates the gaps in research. The second paper builds on the key findings presented in paper one and uses them as model inputs for a system dynamics model. The goal of the system dynamics model is to determine the environmental, sustainability, and financial impact of partially transitioning Missouri's residential electricity portfolio to renewable energy, specifically, solar microgrids.

The third paper presents a cost benefit analysis of using a solar microgrid to partially meet the energy demand of a university building. This collection of works has been developed to aid decision makers at all levels to address global climate change by developing clean energy strategies.

PAPER

I. DETERMINING MICROGRID ENERGY SYSTEMS DYNAMIC MODEL INPUTS USING A SAM ANALYSIS

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ABSTRACT

With a crumbling energy infrastructure, the need for innovative solutions towards grid modernization are imperative. Local and state governments will play a central role in the adoption and regulation of such solutions. This study takes the barriers to entry as determined by a state government and cross references them with the research being conducted in the field of microgrid evaluation through means of a State-of-the-Art matrix (SAM) analysis and integrative literature review. The results of this study indicate that some of the barriers to adoption are adequately covered in the literature while others are not. A system dynamics model is then developed from SAM inputs. These results may be used by engineering managers to formulate experiments to more effectively integrate microgrid energy systems into the national energy infrastructure.

1. INTRODUCTION

The United States' energy infrastructure is in a state of disrepair. The American Society of Civil Engineers has published "report cards" evaluating all facets of the country's infrastructure for decades. In 2017, energy infrastructure received a "D". This grade is a function of several components, but the electricity component's contribution is primarily due to aging infrastructure and economically devastating outages. Fortunately, ASCE provides guidance on how to raise the grade: integration of renewable energy sources and distributed energy generation (ASCE Report Card, 2017).

Currently, renewable energy generation accounts for 10% of all generation compared to 15% for coal, 29% for natural gas, and 37% for petroleum (EIA, 2017). In addition to the economic and reliability issues addressed by the ASCE, the use of conventional energy sources has a considerable impact on the environment by means of greenhouse gas emissions. In 2016, the United States emitted 6511 million metric tons of carbon dioxide equivalents (USEPA, 2018). To adhere to the guidance given by the American Society of Civil Engineers, the United States must increase renewable energy's portfolio share and microgrids have emerged as a potential solution.

The Department of Energy (DOE) defines microgrids as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode" (USDOE, 2012). Given that microgrids can utilize renewable energy sources and serve as distributed energy generation sources, there should be wide-spread adoption.

Technological innovation is not always met with wide-spread acceptance. That said, it is imperative that researchers develop an understanding of specific barriers to adoption to better serve the public on critical technological advancements (Long et al. 2016). As it relates to microgrids, the question becomes: what are the barriers to wide-spread adoption and is the research addressing those areas.

In this study, an integrative literature review is used to analyze and discuss the current state of research related to microgrids and their evaluation. By assessing the literature, this analysis is intended to provide a comprehensive and robust survey of the research being done, identify gaps in the research, and provide future researchers direction. This will be achieved by a State-of-the-art matrix (SAM) analysis of past literature related to microgrids and their evaluation.

2. METHODOLOGY

This study introduces an integrated literature review and SAM analysis to determine if the research being conducted in the field of microgrid evaluation coincides with the barriers associated with the technology adoption.

Local and state governments will continue to play a key part in the adoption of new technologies. Often, they conduct their own analyses to determine what barriers exist for a given technology. An example of this is a 2010 study conducted for the Commonwealth of Massachusetts.

Table 1. presents the barriers of entry and their descriptions (NYSERDA, 2010). Sustainability was added to this paper to provide further depth to the study.

Table 1. Barriers of Entry for Microgrid Adoption

Benefit	**Description**
Direct Economic	Facility energy cost reduction
	Participation in Ancillary Service Markets
	Sales of excess electricity to the macro-grid
	Participation in demand response programs
	Optimization of assets based on pricing signals and real time energy markets
Indirect Economic	Reduced electric T&D losses
	Deferred electric T&D capacity investments
	Support for deployment of renewable generation
Reliability and Power Quality	Ability to operate absent macrogrid
	Reduced facility power interruptions
	Increase power facility electricity reliability
	Ability to operate absent electricity and gas infrastructure
Environmental	Reduced emissions of greenhouse gases
	Reduced emissions of criteria pollutants
Security and Safety	Safe havens during power outages
	Ability to support community during long term outages
Sustainability	Consideration of long-term value of energy conversion
	Analysis of material procurement process

The metrics determined by the study seemed to provide an acceptable representation of the research being conducted. However, the extent to which each metric was being studied was not clear.

Entrepreneurial innovation alone will not be enough to advance microgrid technologies. As the United States' energy infrastructure is currently tied to the macrogrid, so too will its adoption and regulation be tied to the larger regulatory bodies of the United States. The response from local and state governments will be central in developing a sustainable energy future. Thus, the relationship between private enterprise and public regulation is paramount. The question becomes: does the research being conducted adequately address the barriers of entry determined by local and state governments? A state-of-the-art matrix (SAM) was developed to answer this question. SAM's are specifically useful for researchers to identify gaps and trends in the existing literature (Egbue and Long, 2012).

The research conducted primarily used the SCOPUS database and selections were limited to peer-reviewed sources. No filters were put on the search query to demonstrate the evolving nature of the field. The keywords ["microgrid" AND evaluation] were used in the search process. The screening process included a brief analysis of source title, abstract, methods, results, and works cited. After all irrelevant sources were removed, a more in-depth analysis of the remaining works was conducted with specific attention paid to the methods section of each. If the remaining sources contained specific analysis of any of the barriers of entry as previously defined, then they were included in the final SAM model and were marked with an "x" in the corresponding category. Papers were then organized chronologically to demonstrate breadth of given research works as the field evolved. The final SAM model can be found in Table 2.

Table 2. State-of-the-Art Matrix for Microgrid Evaluation

Author	Year	Type	Direct Economic	Indirect Economic	Reliability and Power Quality	Environmental	Sustainability	Security and Safety
Lopes et al.	2005	Journal			x			
Agalgaonkar et al.	2006	Journal	x	x	x	x	x	x
Vallem et al.	2006	Symposium	x	x	x			
Costa and Matos	2006	Conference Proceedings	x	x	x			
Ribarov and Liscinsky	2006	Journal	x					
Zoka et al.	2007	Journal	x		x			
Asanol and Bandol	2007	Conference Proceedings	x	x				
Asano and Bando	2008	General Meeting	x	x	x			x
Yokoyama et al.	2008	General Meeting	x	x	x			
Bae and Kim	2008	Journal	x	x	x			
Marney et al.	2008	IEEE Power and Energy Magazine	x	x	x	x		x
Chakraborty and Simoes	2009	Journal		x	x			
Kennedy and Marden	2009	PowerTech, 2009 IEEE Bucharest		x	x			
Kennedy	2009	General Meeting		x	x			
Kwasinski	2010	Journal	x	x	x			
Pudjianto et al.	2010	Journal	x		x			x
Kakigano et al.	2010	Conference Proceedings		x				
Radwan and Mohamed	2011	Journal			x			x
Lasseter	2011	Conference Proceedings		x	x	x	x	x
Schwaegerl et al.	2011	Journal	x	x	x	x		
Kyriakarakos et al.	2011	Journal	x	x	x			
Stadler et al.	2012	Journal	x			x	x	
Menon et al.	2013	Journal	x	x	x	x		
Kyriakarakos et al.	2013	Journal	x	x	x			
Piacentino et al.	2013	Journal	x			x		
Olivares et al.	2014	Journal		x	x			
Bracco et al.	2014	Journal	x	x	x	x	x	x
Silvestre et al.	2014	Journal	x	x	x	x		
Zeng et al.	2015	Journal		x	x			
Ma et al.	2015	Journal	x	x	x			
Baghaee et al.	2016	Journal	x	x	x	x		
Wang et al.	2016	Journal	x	x	x			
Marzband et al.	2017	Journal	x	x	x		x	
Jin et al.	2017	Journal	x	x	x	x		

3. RESULTS AND DISCUSSION

The search for relevant articles using the previously mentioned methodology yielded 34 articles. Of those articles, 10 were conference proceedings, magazine, or symposium entries and 24 were journal articles. Articles reviewed, but not included in the final SAM model, were excluded due to insufficient attention paid to the topics or were found to be irrelevant in their analysis of evaluating microgrids.

Table 3. demonstrates the extent to which each topic was covered in the literature as a percentage. The summary shows that direct economic benefits (69%), indirect

economic benefits (75%), and reliability (81%) were well-covered in the literature. Conversely; environmental (31%), sustainability (14%), and security and safety (19%%) are topics that need to be researched further.

Table 3. Topics Covered as a Percentage

Benefit	Number of Articles	Percentage
Direct Economic	25	69%
Indirect Economic	27	75%
Reliability and Power Quality	29	81%
Environmental	11	31%
Sustainability	5	14%
Security and Safety	7	19%

To provide chronological context to the study, Figure 1. was developed to show evolution of the research fields as a function of frequency of publications over time. As the figure suggests, there is a decline in the frequency of publication over the last couple of years (2015-2017). This decline could be the function of several things: publications chosen for this SAM, researchers moving on to different topics, funding for research in those areas, etc. While some of the possibilities mentioned are more likely than others, microgrids continue to provide a unique solution to the United States' energy infrastructure and given that widespread adoption has not taken place it is reasonable to assume that the barriers have not been fully-addressed. The following summaries indicate the key positions from the literature in each of these areas.

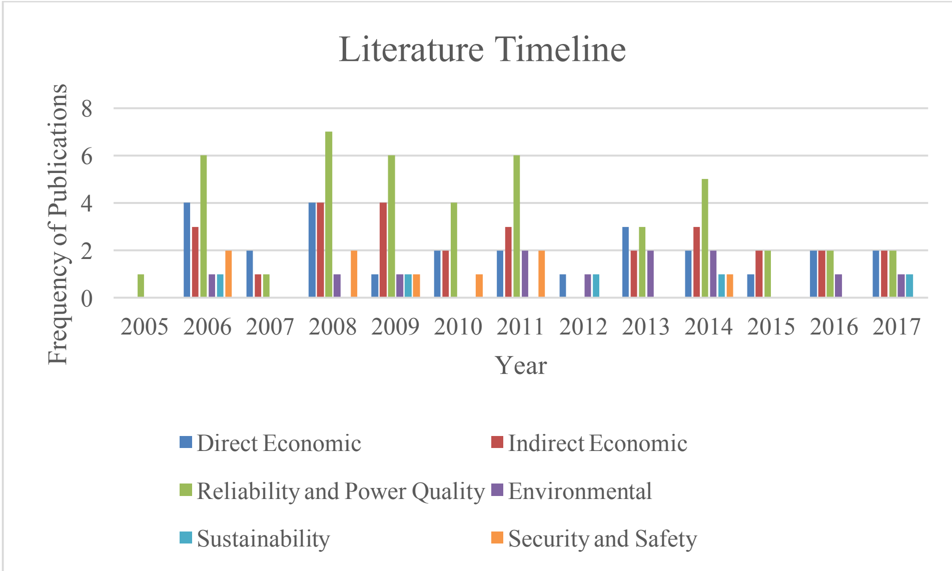

Figure 1. Frequency of Publication by Type Over Time

3.1 DIRECT AND INDIRECT ECONOMIC LITERATURE

A proposed project or innovative technology is often measured by its economic merit. This is accomplished through varying cost benefit analyses that vary in sophistication and scope. Some analyses measure aspects of a project or technology such as decreases in manufacturing cost per watt for a specific material. (Jean et al. 2015) Other analyses measure entire systems such as the Life Cycle Cost analysis presented by Rodriguez et al (Rodriguez et al. 2016). The importance of conducting these analyzes is supported by the SAM developed in this study as 72% addressed direct economic benefits of microgrid adoption and 78% addressed indirect economic benefits.

Except for a few articles, each time the economic contribution was considered it included both direct and indirect economic benefits. Agalgoaonkar et al. (2006) presented an economic analysis that included a cost-benefit analysis, an analytical hierarchy process, and a multi-attribute decision making approach. Bae and Kim (2008) studied the reliability of customers in a microgrid that included cost as an impact factor in a case study format with three different microgrid systems. Some articles, such as Kwasinski (2011), posit studies that don't formally mention cost-benefit analysis but use cost as a common theme throughout the research. Bracco (2014) et al developed a mathematical model to determine optimal operation of a microgrid as a function of technical, economic, and environmental performance indicators.

The SAM demonstrates that the literature covers the direct and indirect benefits of microgrids extensively while accomplishing that aim through varying methods of analyses. The direct and indirect economic literature might seem saturated, but it is vital that research be continued in this field. Economic analysis will continue to be a driving force in the decision-making process toward a sustainable energy future.

3.2 RELIABILITY AND POWER QUALITY LITERATURE

One of the many advantages associated with microgrids is their reliability (Mumtaz and Bayram 2017). As previously mentioned, microgrid reliability in this study is defined as being able to operate in "island" mode or absent from the macrogrid, reduced facility power interruptions, increased power electricity reliability, and the ability to operate without electricity and gas infrastructure. Interest in studying the reliability of systems has increased significantly in recent times in response to outages caused by extreme weather events. Between 2003 and 2012, 679 widespread outages occurred due to extreme weather events (U.S. DOE, OE-417). The United States has experienced 144 severe weather events since 1980 resulting in more than $1 trillion dollars of damage

(U.S Department of Commerce, 2013). Devastation of the economy and livelihood of our citizens will continue to happen until more reliable energy solutions are widely adopted.

Fortunately, reliability was the most covered topic in this study with 81% of articles addressing it. Vallem et al. (2006) developed a Monte Carlo simulation that considered the limited nature of storage devices in their reliability evaluation. Zoka et al. (2007) presented a total cost function that included reliability by integrating power interruption costs. Olivares et al. (2014) posited a mathematical formulation to address the energy management problem associated with isolated microgrids in a centralized energy system.

While reliability and power quality are the most covered topic in the SAM, it is imperative that the topic be studied further. As the literature suggests, they are studied in several ways and specificity of its definition will improve the research being conducted on the topic. Failure to improve upon the reliability and power quality of existing and future technologies will only result in further damage to our economy and citizens.

3.3 ENVIRONMENTAL AND SUSTAINABILITY LITERATURE

The environmental benefits of renewable energy technologies are covered markedly in the literature. Conventional fossil fuels are the biggest crisis to human beings as most our energy comes from them and some will be exhausted in several decades (Ma et al. 2014). One of the primary detrimental characteristics of conventional fossil fuel use is the emitting of CO2 into the atmosphere. Fortunately, CO2 emissions are on the decline. The EIA reported that CO2 estimates have fallen to 5262 million metric tons in 2015, down 12.2% from 2005 (Klein, 2016).

The most widely accepted definition of sustainability is “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations Report of the World Commision on Environment and Development, 1987). Comparable to the environmental benefits addressed in the renewable energy literature, the sustainable advantages of transitioning away from our dependence on conventional fossil fuels is covered at length. Among the reasons to transition away from conventional fossil fuels are geopolitical issues with regards to security and supply and health risks related to their combustion (Mathiesen et al. 2015).

Environmental and sustainable benefits of renewable energy technologies are covered extensively in the literature. However, when looking through microgrid-specific articles those benefits are implicitly implied as matter-of-fact statements and are seldom included in the evaluation of microgrids directly. Of the articles included in the SAM model, only 12 (33%) addressed environmental. Furthermore, sustainability advantages of microgrids were only covered in 9 (14%) of the articles.

Agalgoaonkar et al. (2006) included emissions in their cost-benefit analysis. In their study of policymaking for microgrids, Marnay et al. (2008) addressed societal perspectives and emissions as focal points. Lasseter (2011) addressed the concept of smart distribution through use of hundreds of distributed energy resources and more efficient technologies to better account for waste heat.

It is apparent that further research on environmental and sustainability benefits is required. While these topics are covered extensively in the renewable energy literature, direct translation to microgrids should not be assumed.

Due to their complexity and geographic specificity, the literature would benefit from case studies addressing long-term societal value and environmental impact of microgrids.

3.4 SECURITY AND SAFETY LITERATURE

As technologies continue to develop so too will the sophistication of securities threats. With increased deployment of smart grid technologies, cyber security events are of significant concern (ICF International, 2016). Of the 200 cases of hacking handled by the Department of Homeland Security between October 2012 and May 2013, 53% were on the energy sector (Department of Homeland Security, 2013). National security, business operations, and standard daily activities would all be detrimentally affected if the United States' infrastructure were to be compromised. That said, it is necessary that the security and safety of each distributed energy system be rigorously evaluated.

Safety and security were covered by 9 (25%) of the articles in this study. Asano and Bando (2008), in their economic evaluation study addressed the importance of safety from a regulatory standpoint for distributed energy resources. Pudjianto et al. (2010) posited that maintaining power quality and security in microgrid systems was essential and dependent on the response time of the micro-sources. Bracco et al. (2014) conducted a case study of a smart polygeneration microgrid at the University of Genoa with a primary goal of improving power quality and security.

With security and safety's relationship to national security, more research is required. While safety and security was not the least covered topic in the SAM, its importance as a barrier to adoption cannot be denied. With the potential consequences of a compromised energy infrastructure, security and safety should be a critical research area for the evaluation of microgrids.

3.5 PRELIMINARY SYSTEMS DYNAMICS MODEL

Key findings from the SAM analysis shows that distributed energy resources and smart technologies will continue to play a central role in addressing grid modernization. While some of the barriers to adoption were adequately covered in the literature, others were not. Specifically, environmental impact, sustainability, security and safety have been underused in modeling efforts and shows a strong gap in the literature. One approach to this gap is the development of a systems dynamics model to simulate the effectiveness of large-scale energy transition projects. The model developed would address the shortcomings identified in this research. The model presented in Figure 2. shows sample elements of environmental impact and sustainability as part of an early causal loop diagrams. Next steps include development of feedback loops, as well as stock and flow diagrams. Once the model is formulated, simulations can be performed to demonstrate the impact of changes in the energy portfolio for a state or a region.

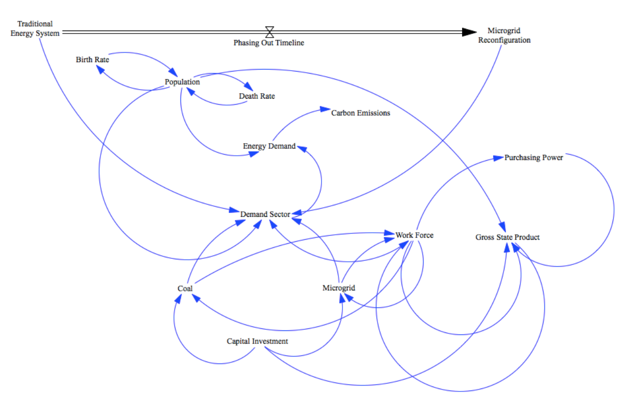

Figure 2. Sample System Dynamics Model

4. CONCLUSIONS AND FUTURE WORK

Although the model in Figure 2 is specific to Missouri's energy infrastructure, it can be easily adjusted to fit the needs of other regions or state to evaluate the impacts of sustainable generation and integration of microgrids or other technologies into the energy portfolio. The systems dynamics model presented can be used to simulate the effect of phasing out coal-firing plants and replacing them with microgrid energy systems.

Future work will finalize the systems dynamics model and develop simulations to see what affect such a transition will have on the work force associated with coal procurement and processing.

Considering the impact on workforce will allow engineering managers to meet the energy demand in wake of the coal-firing plants going offline. It will also provide tools and techniques that can lead to a reduction in carbon emissions, while also considering the impact on Missouri's gross state product.

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II. A SYSTEM DYNAMICS APPROACH TO EVALUATE ENVIRONMENTAL AND SUSTAINABILITY BENEFITS OF TRANSITIONING A RESIDENTIAL ELECTRICITY PORTFOLIO

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ABSTRACT

Dependence on fossil fuels and their subsequent emissions are degrading the environment. Therefore, the need to develop clean energy strategies has never been greater. Governments at all levels will play a central role in the development of these strategies. Unfortunately, there is no single solution that works everywhere given the complexity of energy infrastructures and portfolios. To address this complexity a system dynamics model was developed using the results of an integrative literature review of microgrid energy technology evaluation as model inputs. The model presented evaluates the environmental and sustainability benefits of partially transitioning Missouri's residential electricity demand from coal to microgrid energy systems. The results suggest that emission reductions and decreased dependence on coal would be significant, but the financial investment required would be significant.

The results of this study can be used by city planners or policy maker tasked with determining the systematic impact of a large-scale energy transition project.

1. INTRODUCTION

In a previous study, a state-of-the-art matrix (SAM) analysis was conducted to see if key barriers to adoption for microgrid energy systems were adequately addressed by previous research (Hale and Long, 2018). The results of the study show that environmental impact and sustainability were two key areas that were not sufficiently addressed. A system dynamics (SD) model has been developed to evaluate carbon dioxide emission reductions and decreased dependence on fossil fuels in partially transitioning an energy portfolio. Given the complexity of energy infrastructures, it is imperative to develop solutions that directly address specific sectors. Missouri's residential sector was chosen due to its dependence on coal that is almost entirely sourced from Wyoming.

2. MOTIVATION OF WORK

Located in the Midwest of the United States, Missouri is home to approximately six million people (Census Estimate, 2017). Currently, Missouri relies heavily on coal combustion to meet its electricity demand. In 2017, coal accounted for 81% of Missouri's electricity generation (EIA - Missouri Profile, 2017). The coal combusted to meet the electricity demand is mainly sourced from Wyoming. Table 1. was developed to demonstrate Missouri's dependence on coal from Wyoming by using 2016 procurement data (EIA - Annual Coal Distribution, 2016).

Table 1. Coal Procurement Data

Origin State	**End Sector**	**Short Tons**	**Origin State Total (Tons)**	**% of Total**
Colorado	Industrial Plants Excluding Coke	116130	116130	0.33%
Illinois	Electric Power Sector	356936	846856	2.38%
	Industrial Plants Excluding Coke	433097		
	Commercial/Institutional	56823		
Indiana	Industrial Plants Excluding Coke	171903	171903	0.48%
Wyoming	Electric Power Sector	34479061	34479061	96.81%
		Total	35613950	

As Table 1. demonstrates, Missouri acquires almost 97% of its coal from Wyoming. When considering the electric power sector alone, the number is almost 99%. The average delivered price of coal to the power sector is $42.58/short ton which results in more than $1.5 billion spent on procuring coal from Wyoming annually (EIA, Coal Prices).

Currently, Missouri is ranked 13th in the United States for carbon dioxide emissions. When normalizing for population, Missouri drops to 18th (EIA – Emissions Rankings, 2017). Two of the top emissions producing states, Wyoming and West Virginia, are also the two highest coal producing states with respect to meeting the nation's demand at 41% and 11%, respectively (EIA – Highest Coal Producing States, 2017). Given these high rankings, it is reasonable to conclude that the supply chain of natural resource procurement and delivery is responsible for a considerable portion of a state's emission profile. In determining the reduction in emissions transitioning an energy portfolio would provide, the value generated throughout the supply chain should also be considered.

In November 2008, Missouri passed the Missouri Clean Energy Act requiring investor-owned utilities to use eligible renewable energy technologies to meet 15% of their annual retail sales by 2021 (EIA - Renewable Energy Standard, 2008). In 2015, renewable energy accounted for just 3.7% of Missouri's net electricity generation. Meeting the 15% benchmark determined by the Missouri Clean Energy Act by 2021 presents a financial challenge that will produce substantial environmental benefits. SD presents an ideal approach to determine the environmental impact, sustainability benefit, and financial investment required of fulfilling the renewable energy standard.

3. LITERATURE REVIEW

Recently, SD has been used to approach a wide range of environmental and sustainability problems. As SD research is continued, models become more robust and comprehensive in their ability to accurately model complex systems. While the methodologies vary from one model to the next, there is a clear observable trend in the improvement of model development. The work presented here furthers previous SD research.

The literature contains several case studies that model renewable energy integration and the subsequent reduction of CO_2 emissions. One such study in Ecuador concluded that it was possible to control CO_2 emissions while simultaneously increasing the gross domestic product (Robalino-Lopez et al., 2014). Another study conducted in Bejing, China uses the STELLA platform to model carbon dioxide emissions in relation to growing energy demands. The study concluded that change in economic development mode and population growth control would have a significant effect on energy consumption and emissions (Feng et al., 2013).

The literature is effective in quantifying the relationship between population growth, energy consumption, and the CO_2 emissions that result, however existing research fails to consider the importance of household size when compared to total population. This research considers the change in specific household populations sizes compared to the total population, as well as emissions throughout the natural resource supply chain. Further, electricity demand and the aggregate emissions of the supply chain are not fully addressed in the literature; this model addresses this gap in the literature as well.

The research takes a case study approach and considers the shift in household size, household electricity consumption, aggregate emissions throughout the coal supply chain in meeting the electricity demand, and the cost to partially transition from coal-dependency to renewable energy to meet the renewable energy standard of 15% in Missouri.

4. METHODOLOGY

SD is an approach that recognizes that system structure – the many complex relationships, sometimes time-delayed – are equally important in modelling a system's behavior as the individual components themselves. The goal of system dynamics is further understanding of internal structure of the system and leveraging this understanding (Sterman, 2000).

4.1 MODEL DESCRIPTION

Residential electricity demand is a product of the number of residential customers and the consumption rate per customer. Some living arrangements are more efficient than others. Given the decrease in the average household size over the last few decades, it is reasonable to assume that we will continue to trend towards smaller household sizes (Historic Household Tables, 2017). Therefore, it is necessary to determine the size of specific household populations. The amount of coal required and renewable energy generated will change with the electricity demand. Any change in the demand for coal would affect the entire supply chain and its subsequent emissions. Further, use of these relationships in developing the SD model is justified.

In this study, the SD model shown in Figure 1. includes five subsystems: population, household population and electricity demand, electricity demand fulfillment, coal supply chain and fugitive emissions, and total cost. A full listing of the equations that govern these subsystems can be found in Appendix A. Once integrated, the SD model will evaluate the reduction in carbon dioxide emissions, decreased dependency on coal, and total cost associated with partially transitioning Missouri's residential electricity portfolio to meet the renewable energy standard of 15%. Before the simulation can be run, however, data must be collected that accurately represents the system.

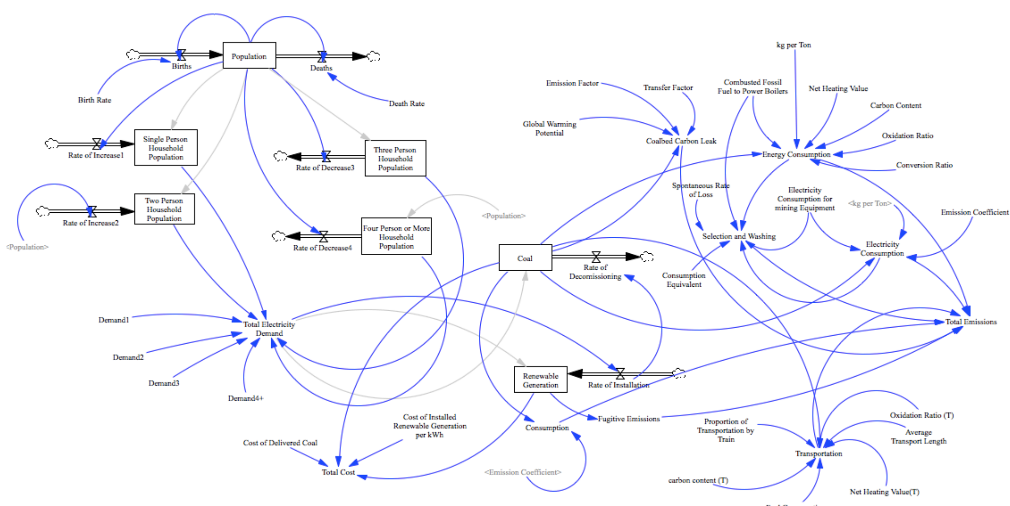

Figure 1. SD Model of Missouri's Residential Electricity Fulfillment

4.2 DATA COLLECTION

The data used to develop and validate the model comes from several sources. Whenever possible, Missouri-specific data was used. Due to the proprietary nature and shortage of such data, national and publicly available data was often used to develop nominal data sets. The methodology used to develop those data sets is presented in the next section.

Some of the data used to develop the model was gathered from governmental organizations. Population, birth rate, and death rate data was procured from previously cited census data and the Missouri Department of Health and Senior Services (MDHS, 2017). There was no data available demonstrating the specific household population size for Missouri. Therefore, the Historical Household Tables from the Census Bureau were used (Census Bureau, 2017). The Energy Information Administration (EIA) provided several data inputs: national household consumption data from the Residential Energy Consumption Survey (RECS, 2015), Missouri's energy portfolio specifics (EIA, 2017), and the cost of delivered coal (EIA, 2015). Lastly, data gathered from the Wyoming Geological Survey (WGS) was used to determine the type of mines prevalently used in Wyoming (WGS, 2017). The remainder of the data was gathered from peer-reviewed research articles and non-governmental organizations.

There were a few sources used outside of governmental organizations. The largest, single-source contributor to the model was the coal supply chain analysis conducted by (Luo et al., 2017).

The total emissions component of the model was derived from their study with a few notable exceptions: fugitive emission from renewable generation gathered from (OECD, 2007), proportion of transportation by railroad (EIA -Annual Coal Distribution, 2017), average transport length (Missouri Economic Research and Information Center, 2002). A comprehensive list of the values used can be found in Appendix B.

4.3 DEVELOPMENT OF NOMINAL DATA SETS

Two nominal data sets were developed for the model. First, the percentage share of specific household populations to the entire population was determined using the historic household tables from the Census Bureau. Using data from 1960-2017, Holt's Method was implemented to forecast values for the next thirty years. Put simply, Holt's Method is a forecasting analysis that adjusts for changes in level and trend of the data. The mean average percentage error (MAPE) of each data set is included to demonstrate accuracy of the results. The population shares of each individual group can be found in Table 2. and the forecasted values from Holt's Method can be found in Appendix C.

Table 2. Change in Population Share Over 30 Years

Group	% of Population at t = 0	% Change Over 30 Years
1	11.36%	2.08%
2	28.03%	5.67%
3	18.86%	-0.73%
4	20.89%	-3.00%
5	11.79%	-2.28%
6	5.41%	-0.42%
7	3.66%	-1.32%

To further demonstrate the environmental impact of growth in smaller household populations, four-person, five-person, six-person, and seven-person or more housing populations were combined. In doing so, the weighted consumption and growth rates of the new group were determined as shown in Table 3. and Table 4., respectively.

Table 3. Weighted Change in Population Share Over 30 Years

Group	**% of Population t = 0**	**Weighted % Change Over 30 Years**
4	20.89%	-
5	11.79%	-
6	5.41%	-
7	3.66%	-
4 or More	41.75%	-2.14%

Table 4. Weighted Residential Electricity Consumption by Household Size (EIA, Residential Data)

<table>
<tr><td colspan="5">United States Residential Electricity Consumption</td></tr>
<tr><th>Number of Household Members</th><th>Total (billion kWh)</th><th>Population (billions)</th><th>kWh/member/year</th><th>kWh/member/year (weighted)</th></tr>
<tr><td>1 member</td><td>138.1</td><td>0.03602113</td><td>3833.860854</td><td>-</td></tr>
<tr><td>2 members</td><td>307.4</td><td>0.087781392</td><td>3501.881113</td><td>-</td></tr>
<tr><td>3 members</td><td>147.6</td><td>0.058833338</td><td>2508.781672</td><td>-</td></tr>
<tr><td>4 members</td><td>137.4</td><td>0.06524193</td><td>2106.007592</td><td rowspan="3">1956.343218</td></tr>
<tr><td>5 members</td><td>73.8</td><td>0.037129801</td><td>1987.621743</td></tr>
<tr><td>6 or more members</td><td>44.2</td><td>0.028177958</td><td>1568.601928</td></tr>
</table>

5. RESULTS AND DISCUSSION

The SD model was developed to evaluate the benefits of partially transitioning residential electricity demand dependence. Three simulations are presented below. The first simulation evaluates the transition over a 30-year period, the second over a 15-year period, and the last over a five-year period. The results below pertain specifically to population, electricity demand, demand fulfillment, total emissions, and total cost.

Table 5 is an output table showing population growth over 30 years. The population growth is linear due to constant birth and death rate values. The population is expected to reach 6.68 million over the next thirty years representing an increase of five-hundred and seventy thousand people as shown in Table 5.

Table 5. Vensim Population Output Table

Time (Year)	**Population**
0	6.11E+06
5	6.20E+06
15	6.39E+06
30	6.68E+06

Energy demand is a more complex calculation as it combines the population subsystem with the housing population subsystem. This is true for the rest of the comprehensive system as one subsystem is integrated with the next. As the table below suggests, population will result in an increase for the demand of electricity from the residential sector as shown in Table 6. The purpose of multiple simulations is demonstrated when the electricity demand fulfillment is considered. The smaller the time to complete the portfolio transition, the greater the downstream stress. The rest of the discussion will address the outputs for each simulation to better explain the effect time has on the system.

Table 6. Total Electricity Demand Output Table

Time (Year)	**Total Electricity Demand (kWh)**
0	1.65E+10
5	1.68E+10
15	1.72E+10
30	1.79E+10

The population and total electricity demand will behave as previously mentioned. Initially, coal accounts for 81% of electricity and solar energy for 2%. The remainder of Missouri's electricity portfolio is met by a combination of nuclear and other non-renewable sources considered outside of this study's scope (EIA, Missouri Profile). The model installs solar energy as it reduces coal's portfolio share. To achieve Missouri's renewable energy standard of 15%, coal's portfolio share is decreased by 13% over the course of the simulation and solar energy's share is increased by the same amount. To better represent this relationship over time, a graphical representation of the change is presented in Figure 2. Given the linear relationships established in the SD model, the result of each simulation will be the same. The difference between each simulation is the time given to conduct the portfolio transition. The same trend can be observed in both the total emissions and total cost as seen in Figure 3. and Figure 4.

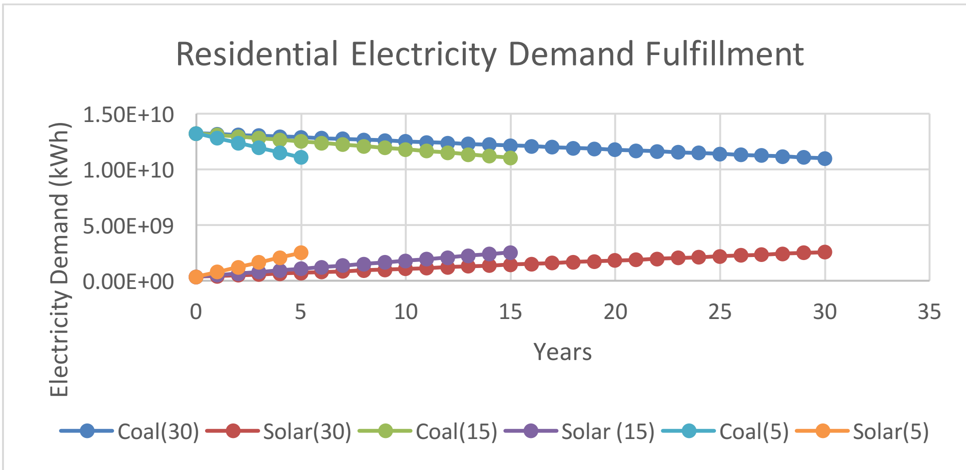

Figure 2. Residential Electricity Demand Fulfillment Comparison

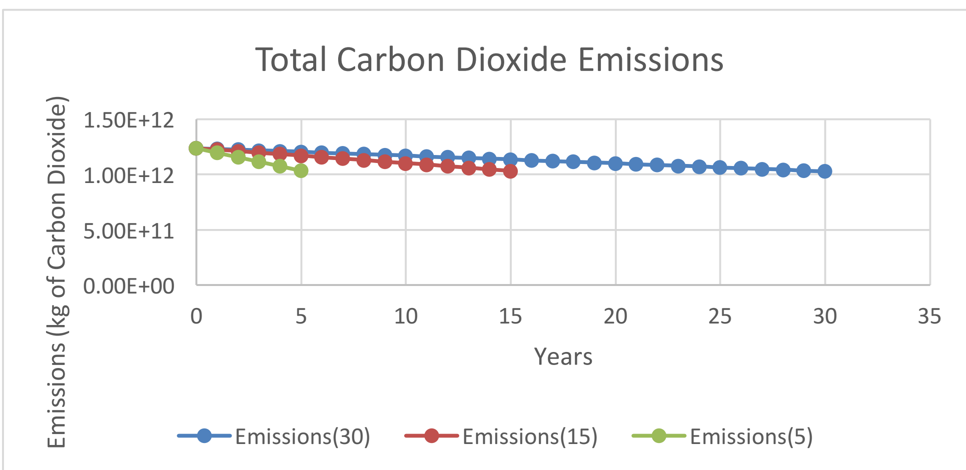

Figure 3. Total Carbon Dioxide Emissions Comparison

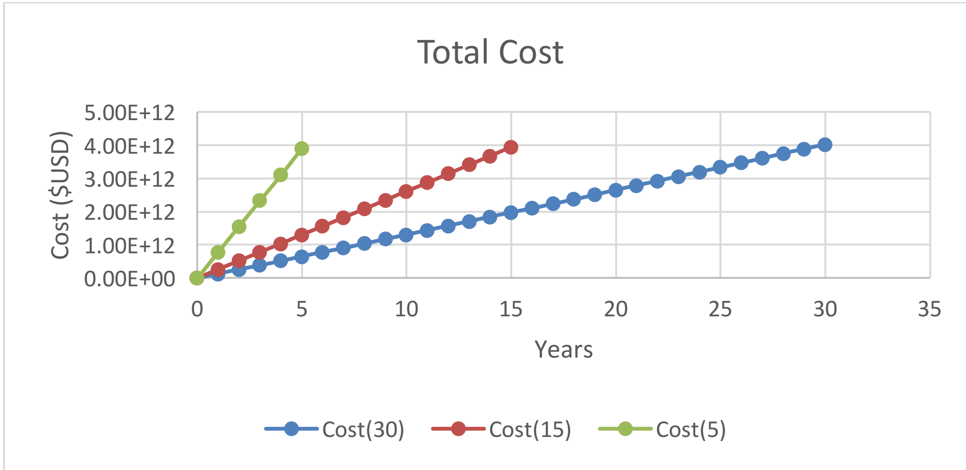

Figure 4. Total Cost Comparison

The results of the model present the following findings. First, population is projected to increase in the coming years. As the population increases, the number of people living in one or two person homes will increase while all other household sizes decrease their market share. Given that electricity consumption per household member decreases as the total members in the household increase, it can reasonably be determined that demand for electricity will not only increase due to population growth, but also because residents are trending towards smaller household sizes. Second, when the entire supply chain including end consumption is considered the environmental impact of coal dependency is significant. The transition proposed would result in a reduction of carbon dioxide emissions of 170 billion kilograms. Third, microgrid energy systems are not presently cost effective. While the cost for coal remains low and accessibility is not hindered it will be difficult to justify this transition. The results vary little between the three simulations with the total cost being approximately four trillion dollars. While this may seem a ludicrous number, when compared to the environmental benefits it comes to $23.50 per kilogram of carbon dioxide removed from the atmosphere.

This model presents a framework for evaluating the collective environmental, sustainability, and financial impact of a large-scale energy transition project. Parties that would find utility in such findings include the private citizen considering the merit of installing a rooftop solar system, an engineering manager determining the feasibility of a renewable energy project, the city planner in determining the comprehensive impact of transitioning large portions of the energy portfolio, and the policy maker in determining what policies need to be in place to justify such a transition across financial and environmental boundaries. Unfortunately, this model does not produce outputs that directly correlate with actual data. Future work will address key limitations of the model and produce an updated version that will better serve those mentioned previously.

6. LIMITATIONS AND FUTURE WORK

Several liberties were taken in the development of the SD model and resulted in the following model limitations. Due to the proprietary nature of some of the required data, national and publicly available data was used. Specifically, the household population data was not consistent with historical population values. The earliest value in the data set, 1960, only accounted for 95% of the population in the United States at the time. This trend only got worse as the data approached the present. This discrepancy could be attributed to several factors: error in reporting, more than the allotted number of people living in each household (i.e. four people living in a household for three or vice versa), or the total population data accounting for homeless people while the household data understandably did not. Additionally, national data was used in determining the electricity consumption per household member per year.

In determining the market share of each household population, certain consistent decisions were made that affect the forecasted data. As mentioned previously, Holt's forecasting method was used to determine the growth of each of the household population sizes. Holt's method forecasts future demand when there is trend present in the data. Use of Holt's method requires the determination of two smoothing constants, alpha and beta and their values are between zero and one. Typically, a linear program is run to optimize one of several statistical evaluation values attributed to your data set such as mean square error or mean average percentage error. When the linear programs were run both alpha and beta diverged toward the extreme values. The closer the smoothing constant is to one, the quicker it responds to changes in the time series. To address this inconsistency, the value of 0.5 was used for both alpha and beta throughout the analyses.

The equations that govern the behavior of the model present a couple of limitations to the study. First, the use of linear causal relationships throughout the model resulted in an oversimplification of an extremely complex system. Second, there was little available data to determine where household members previously living in larger households went once they left. If data could be procured that approximated the probability that someone would leave one household for another, then the relationship between the household size populations would be given validation beyond the statistical values used in the forecasting analysis. Lastly, there is no feedback loop present in the model. As feedback loops are a cornerstone of SD models, this presents a significant shortcoming to the work.

Research is not a static enterprise and as such neither is this model. Future work will include the following. Procurement of Missouri-specific data that is gathered for the expressed use of modelling an energy transition project. Such data would eliminate the need to develop nominal data sets and provide more accurate results. Further sensitivity analysis might result in the determination of more accurate smoothing constants. The greater the accuracy of the smoothing constants, the greater the value of the forecasted data. The discovery and development of both non-linear causal relationships and feedback loops would provide further accuracy to the model. The work presented here provides a promising first step towards modelling Missouri's energy infrastructure. If the future work is successful in addressing the limitations identified previously, then the model can be implemented to model transition projects in urban versus rural communities, developed vs undeveloped communities, and even pivoted to account for a different primary energy source and its supply chain. Regardless of the future shape this model takes, it is safe to conclude that SD will continue to serve a role in the development of a sustainable energy future.

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III. MICROGRID IMPLEMENTATION OF A ROOFTOP PHOTOVOLTAIC SYSTEM

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ABSTRACT

In recent years, the demand for alternative energy options has increased. Countries and communities alike are diversifying their energy portfolios by integrating renewable energy technologies to better serve their end users and the environment. Microgrids have emerged as a possible solution to addressing diversification. This research presents a cost analysis in implementing a rooftop solar photovoltaic system in Missouri as part of the energy management approach on a university campus. Given the size and energy requirement of the building, as well as the installment plan, the system operates as a microgrid. The cost analysis conducted includes a standard and discounted payback period. This study may be used by the engineering manager to implement solar photovoltaic rooftop systems in similarly sized buildings with comparable energy demands.

1. INTRODUCTION

1.1 MICROGRID SOLAR PHOTOVOLTAIC SYSTEMS

Microgrid Solar Photovoltaic (PV) systems are an increasingly prevalent energy source. Through direct (solar radiation) and indirect (wind, biomass, hydro, ocean etc.) forms, solar energy is the most abundant resource available. Approximately 60% of the sun's energy reaches the earth's surface. If a marginal 0.1% of this energy could be converted at an efficiency of 10%, then the result would be four times the world's current electricity generating capacity of approximately 5000 GW (World Energy Council, 2013). Given the wide availability of the resource, increasing efficiency of technology, and declining cost of associated materials it is likely that microgrid solar PV systems will continue to increase their market share.

This study considers the implementation of a microgrid solar PV system at a building on the Missouri University of Science and Technology (Missouri S&T) campus in Rolla, Missouri. The system operates as a microgrid due to the size of the building as well as the installment plan. Missouri S&T acquires its electricity from Rolla Municipal Utilities (RMU), a local utility provider. RMU is required to purchase power through the Missouri Public Energy Pool. However, there is an exception through the Net Metering and Easy Connection Act. The Net Metering and Easy Connection Act has stringent limits. Among those limits is the requirement that the total output of all systems owned by one customer be no larger than 100 kW (Net Metering and Easy Connecton Act, 2010). This work focuses on providing the engineering manager with a decision framework for implementing a rooftop microgrid PV system. A model is built to calculate the payback period of the system using a standard and discounted method for comparison. This model enables the engineering manager to make an informed financial decision regarding similar energy transition projects.

2. MOTIVATION OF RESEARCH

2.1 UNITED STATES INFRASTRUCTURE REPORT CARD

In 2017, the American Society of Civil Engineers (ASCE) executed a comprehensive multidisciplinary analysis of the United States' infrastructure. The energy component of the report earned a D+. This grade can be largely attributed to aging infrastructure and resiliency issues in the face of severe weather events. In 2015, 3571 total outages were reported with an average duration of 49 minutes per outage. Between 2002 and 2012, power outages are estimated to have cost the U.S. economy an inflation-adjusted annual average of $18 to $33 billion (ASCE Report Card, 2015).

2.2 A DIVERSE ENERGY PORTFOLIO

A solution to the problems highlighted by the ASCE is to modernize the energy grid. Modernizing the energy grid will most effectively be addressed by the wide-spread deployment of energy diversification and efficiency improvement projects that will result in a "smart grid". The smart grid will possess a chain of interconnected networks of distributed energy systems known as microgrids that will function whether they are tied to or isolated from the electricity grid. Functionality when not tied to the grid will require the integration of renewable technologies. Furthermore, the smart grid will empower end-users by implementing demand-side management strategies that will enable them to better manage their energy uses resulting in cost savings (Farhangi, 2010).

3. LITERATURE REVIEW

The transition from conventional to renewable energy sources has been a subject of interest for decades. In the last decade, research and implementation of energy transition projects has increased due to improvements in renewable energy technology and cost. Due to these improvements, the literature on solar microgrid PV systems has grown considerably.

3.1 MICROGRID SOLAR PV SYSTEM ADVANCEMENT

In recent times, photovoltaic technologies have increased their global market share considerably. Annual domestic installations increased at an average rate of 68% between 2006 and 2016. The increase can be attributed to innovation and decreasing costs associated with the solar investment tax credit (SEIA, 2017) Solar PV additions reached 2016 GW in 2016, making the United States the third largest market globally. (International Energy Agency, 2016). Currently, 373,807 Americans spend some portion of their time on solar related technologies across the country. Between 2000 and 2016, those Americans working at least partially on solar related technologies accounted for an employment growth rate of more than 300% in the field of solar jobs (Department of Energy, 2017).

Solar energy's increase in market share and job growth in the field suggest a simple conclusion: solar energy's market share and affordability will continue to increase as new technologies are developed and implemented.

3.2 RESILIENCY OF MICROGRID SOLAR PV SYSTEMS

One of the primary advantages of microgrid systems is that they are decentralized power sources. As mentioned in the ASCE infrastructure report card, the United States experiences considerable power outages that result in disastrous economic effect. Billions of dollars are lost annually in lost wages, spoiled inventory, grid damages, and other sources. Investing in a decentralized energy system will increase the grid's resiliency. Increased resiliency will result in less time spent getting critical facilities such as hospitals, shelters, and waste water treatment facilities back online (National Renewable Energy Laboratory, 2014). Increasing microgrid system installations directly translates to increased electricity system resiliency which improves safety, quality of life, and access to basic human needs while simultaneously saving billions of dollars.

3.3 ECONOMIC ANALYSIS OF MICROGRID ENERGY SYSTEMS

The benefits of a microgrid energy system are measured in several ways: reliability, resilience, environmental, performance, efficiency, economic, etc. Economic analyses within the literature vary in scope and intent. Wang et al. posited metrics for assessing the reliability and economic benefit of microgrids using Monte Carlo simulations (Wang et al., 2013). Hatziargyriou et al. presented cost-specific benefits in the way of annual cost reductions using probabilistic analysis techniques (Hatziargyriou, 2011).

A review of the literature has demonstrated that the benefits of microgrid energy systems are measured in several ways. The analyses conducted vary greatly in scope and complexity, but there remains ample room in the literature for additional case studies using simplified economic measuring techniques that can be easily implemented by the engineering manager in a timely manner.

4. METHODOLOGY

This study presents a simplified technique that can be used readily to determine initial profitability of microgrids that can be used as stand-alone or modular systems that can be integrated into the grid. For this work the capital cost of implementing a microgrid solar PV system into an existing building is considered. The building used to model this potential system is on mid-sized campus in the Midwest. To be specific, the Toomey Hall building on the Missouri S&T campus. Engineering economic principles such as time value of money, discount rate, payback period, and discounted payback period were used.

4.1 SYSTEM FEASIBILITY

This research used two methods for evaluating the economic viability of an energy transition project: payback period and discounted payback period. The standard payback period simply considered the total capital investment and the time required to recoup the investment. The discounted payback period performed the same task, but considered the time value of money.

4.2 DATA COLLECTION

The Data used in this study was collected from two sources: Facilities Operations at S&T and the National Renewable Energy Lab (NREL). Facility Operations provided the energy demand data for Toomey Hall over a 12-month period from July 2015 - June 2016 as shown in Table 1. As the table suggests, the monthly power demand for the Toomey Hall building is 207,023 kWh. The maximum system size that can be installed on the campus is 100 kW. Thus, the microgrid solar PV system in question would only partially fulfill the energy demand of the building.

Table 1. Toomey Hall Billing Cycle July 2015 - June 2016

			POWER (kWh)		
		PRESENT -	PREVIOUS x	MULT. =	USAGE
July-15	TOOMEY HALL	660,006.1	390,133.4	1	269,873
August-15	TOOMEY HALL	961,749.1	660,006.1	1	301,743
September-15	TOOMEY HALL	1,180,607.0	961,749.1	1	218,858
October-15	TOOMEY HALL	1,355,786.0	1,180,607.0	1	175,179
November-15	TOOMEY HALL	1,526,117.0	1,355,786.0	1	170,331
December-15	TOOMEY HALL	1,750,521.0	1,526,117.0	1	224,404
January-16	TOOMEY HALL	1,935,234.0	1,750,521.0	1	184,713
February-16	TOOMEY HALL	2,120,771.0	1,935,234.0	1	185,537
March-16	TOOMEY HALL	2,293,251.0	2,120,771.0	1	172,480
April-16	TOOMEY HALL	2,484,665.0	2,293,251.0	1	191,414
May-16	TOOMEY HALL	2,661,462.0	2,484,665.0	1	176,797
June-16	TOOMEY HALL	2,874,406.0	2,661,462.0	1	212,944
				Average kWh/ Month	207,023

NREL's online system performance estimator, PV Watts, was used to analyze the performance of a 100-kW system in accordance with Missouri State Law. The performance estimator requires inputs for the following metrics: DC System Size (100 kW), Module Type (Standard), Array Type (Fixed Open Rack), System Losses (14%), Tilt (20 deg), Azimuth (180 deg), System Type (Commercial), and Average Cost of Electricity Purchased from Utility ($0.09/kWh) ((PV Watts, 2017). Once the values have been submitted, the estimator will return the results of the system. For this given system, the annual cost savings would be $12,889. This value was calculated using the commercial tariff where the average cost of electricity purchased is $0.09/kWh. Missouri S&T, an industrial customer, qualified for a tariff of $0.085/kWh given information provided by RMU below. The decrease in tariff value decreased the annual energy savings to $12,172.94.

5. MODEL

Before either payback period model could be developed, an estimate of the initial investment for the system had to be made. Using limited available market data, the investment was calculated by adhering to a maximum system size of 100 kW and used average cost values associated with 10 kW systems, set up, and additional components needed to make the system operational as show in Table 2. As the table shows, an initial investment of $180,000.00 would be required to set-up a 100kW microgrid solar PV system.

Table 2. System Set-Up Cost

Power provided from PV KW/per month		100
Cost of 10 kW PV System approx.	$	15,000.00
Number of PV System setup required		10
Cost of Setup	$	150,000.00
Inverter, cabling, installation and accessories approx.	$	30,000.00
Total Cost	**$**	**180,000.00**

5.1 MODEL EQUATIONS AND FORMULATION

The model is developed using payback period as the primary decision making component for the engineering manager. Tables 3. and 4. below show the payback period and the discounted payback period, respectfully.

The standard payback period is calculated using Equation 1:

$$\text{Payback Period} = \frac{Initial\ Investment}{Cash\ Inflow\ per\ Period} \tag{1}$$

For the standard payback period and the discounted payback period, the initial investment is $180,000.00. The cash inflow per period is the annual cost savings associated with implementing the system: $12,172.94. As table 3 shows, the payback period for this system is 14.79 years. Table 4 shows the discounted payback period.

The discounted payback period is calculated using Equation 2:

$$\text{Discounted Cash Inflow} = \frac{Actual\ Cash\ Inflow}{(1+i)^{r}} \qquad (2)$$

Where,

r = The Discount Rate

n = Period of the Cash Inflow.

The discount rate for the discounted payback period calculation is set at 5%. All other inputs remaining the same, the discounted payback period for the system was 27.56 years.

Table 3. Payback Period

Payback Period (Time value of money not considered)				
r =	0%			
Year	Amount	PV CF	Balance	
0	$ (180,000.00)	$ (180,000.00)	$ (180,000.00)	
1	$ 12,172.94	$12,172.94	$ (167,827.06)	
2	$ 12,172.94	$12,172.94	$ (155,654.12)	
3	$ 12,172.94	$12,172.94	$ (143,481.18)	
4	$ 12,172.94	$12,172.94	$ (131,308.24)	
5	$ 12,172.94	$12,172.94	$ (119,135.30)	
6	$ 12,172.94	$12,172.94	$ (106,962.36)	
7	$ 12,172.94	$12,172.94	$ (94,789.42)	
8	$ 12,172.94	$12,172.94	$ (82,616.48)	
9	$ 12,172.94	$12,172.94	$ (70,443.54)	
10	$ 12,172.94	$12,172.94	$ (58,270.60)	
11	$ 12,172.94	$12,172.94	$ (46,097.66)	
12	$ 12,172.94	$12,172.94	$ (33,924.72)	
13	$ 12,172.94	$12,172.94	$ (21,751.78)	
14	$ 12,172.94	$12,172.94	$ (9,578.84)	
15	$ 12,172.94	$12,172.94	$ 2,594.10	**14.79**
16	$ 12,172.94	$12,172.94	$ 14,767.04	
17	$ 12,172.94	$12,172.94	$ 26,939.98	
18	$ 12,172.94	$12,172.94	$ 39,112.92	
19	$ 12,172.94	$12,172.94	$ 51,285.86	
20	$ 12,172.94	$12,172.94	$ 63,458.80	
21	$ 12,172.94	$12,172.94	$ 75,631.74	
22	$ 12,172.94	$12,172.94	$ 87,804.68	
23	$ 12,172.94	$12,172.94	$ 99,977.62	
24	$ 12,172.94	$12,172.94	$ 112,150.56	
25	$ 12,172.94	$12,172.94	$ 124,323.50	

Table 4. Discounted Payback Period

Discounted Payback Period				
r =	5%			
Year	Amount	PV CF	Balance	
0	$ (180,000.00)	$ (180,000.00)	$ (180,000.00)	
1	$ 12,172.94	$11,593.28	$ (168,406.72)	
2	$ 12,172.94	$11,041.22	$ (157,365.51)	
3	$ 12,172.94	$10,515.44	$ (146,850.07)	
4	$ 12,172.94	$10,014.71	$ (136,835.36)	
5	$ 12,172.94	$9,537.82	$ (127,297.54)	
6	$ 12,172.94	$9,083.64	$ (118,213.91)	
7	$ 12,172.94	$8,651.08	$ (109,562.82)	
8	$ 12,172.94	$8,239.12	$ (101,323.70)	
9	$ 12,172.94	$7,846.79	$ (93,476.91)	
10	$ 12,172.94	$7,473.13	$ (86,003.78)	
11	$ 12,172.94	$7,117.27	$ (78,886.52)	
12	$ 12,172.94	$6,778.35	$ (72,108.17)	
13	$ 12,172.94	$6,455.57	$ (65,652.60)	
14	$ 12,172.94	$6,148.16	$ (59,504.44)	
15	$ 12,172.94	$5,855.39	$ (53,649.05)	
16	$ 12,172.94	$5,576.56	$ (48,072.48)	
17	$ 12,172.94	$5,311.01	$ (42,761.47)	
18	$ 12,172.94	$5,058.11	$ (37,703.36)	
19	$ 12,172.94	$4,817.25	$ (32,886.11)	
20	$ 12,172.94	$4,587.85	$ (28,298.26)	
21	$ 12,172.94	$4,369.38	$ (23,928.88)	
22	$ 12,172.94	$4,161.32	$ (19,767.56)	
23	$ 12,172.94	$3,963.16	$ (15,804.40)	
24	$ 12,172.94	$3,774.44	$ (12,029.96)	
25	$ 12,172.94	$3,594.70	$ (8,435.26)	
26	$ 12,172.94	$3,423.53	$ (5,011.73)	
27	$ 12,172.94	$3,260.50	$ (1,751.23)	27.56
28	$ 12,172.94	$3,105.24	$ 1,354.01	
29	$ 12,172.94	$2,957.37	$ 4,311.38	
30	$ 12,172.94	$2,816.54	$ 7,127.92	
31	$ 12,172.94	$2,682.42	$ 9,810.35	
32	$ 12,172.94	$2,554.69	$ 12,365.03	
33	$ 12,172.94	$2,433.04	$ 14,798.07	
34	$ 12,172.94	$2,317.18	$ 17,115.25	
35	$ 12,172.94	$2,206.84	$ 19,322.08	
36	$ 12,172.94	$2,101.75	$ 21,423.83	
37	$ 12,172.94	$2,001.67	$ 23,425.50	
38	$ 12,172.94	$1,906.35	$ 25,331.85	
39	$ 12,172.94	$1,815.57	$ 27,147.42	
40	$ 12,172.94	$1,729.11	$ 28,876.53	

6. PRELIMINARY DISCUSSION AND CONCLUSION

This paper outlines the financial analysis that should accompany the consideration of an energy transition project. There is significant disparity between the two models presented. That disparity is predicated on the incorporation of a discount factor into the discounted payback period that accounts for the time value of money. If an engineering manager decides to base their decision on the discounted payback period model, then they will be tasked with selecting a suitable discount factor for their given project. The difference that the discount factor makes in calculating the payback period cannot be stressed enough. Figures 1. and 2. are the graphical representations of the payback period and discounted payback period presented in this paper. To illustrate how critical the selection of a suitable discount factor is, Figures 3. and 4. were developed.

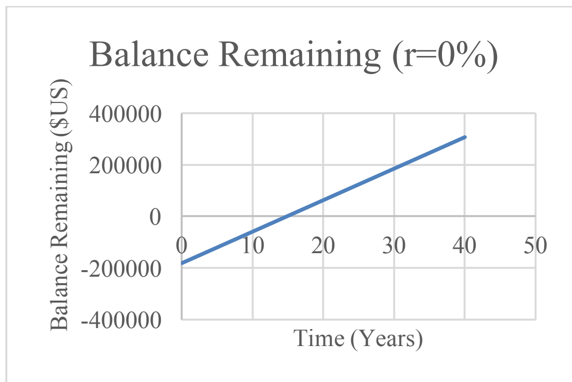

Figure 1. Balance Remaining for Standard Payback Period

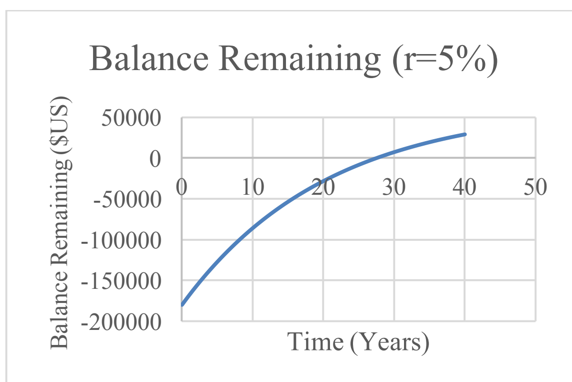

Figure 2. Balance Remaining for Discounted Payback Period when r=5%

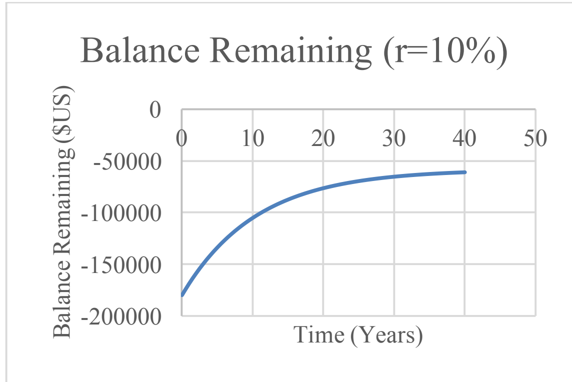

Figure 3. Balance Remaining for Discounted Payback Period when r=10%

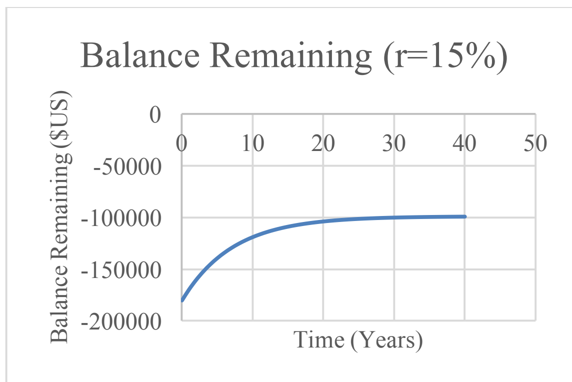

Figure 4. Balance Remaining for Discounted Payback Period when r=15%

As the figures suggest, a discount rate of greater than 5% moves the project into the infeasible range. The results are not immediately promising. However, they are subject to limited available market data. Any change in initial cost estimates, annual savings estimates, efficiency of solar cell technologies, or Missouri energy policies would change the payback period calculations.

7. FUTURE WORK

This study can be used as a rudimentary template by engineering managers to better understand the financial components of energy transition projects and further inform their decision making. The results presented here, while not currently promising, afford future researchers upward mobility. Future researchers will address the materials used and their inherent efficiencies and consult licensed professionals to ascertain more accurate initial cost and performance estimates. Additionally, researchers will also consider implementing an energy storage technology as part of the energy transition project. Refining these components will result in payback periods that are well within the lifetime of the system and will allow the engineering manager to more readily consider energy transition projects.

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SECTION

2. CONCLUSION

The findings presented in this work demonstrate that development of clean energy strategies is a complex process. While it is logical to develop policies at a national level, it may not be so to enact them at the local level. Site-specific studies regarding impact to job markets, the economy, change in cost of delivered electricity, the environment, changes in operational and maintenance costs, and useful life of installed systems are but a few of the analyses that predicate change. Each of the analyses should be evaluated on their individual merit in addition to net benefits provided to society. This work was conducted with the expressed goal of determining the net benefit of wide-spread microgrid adoption in the state of Missouri. To determine how this work was in accomplishing that goal, the findings of each paper must be revisited and evaluated comprehensively.

In the first paper, the SAM analysis conducted determined that present and on-going research adequately addressed some key barriers to adoption for microgrid energy systems. In reviewing more than thirty peer-reviewed research articles it was clear that environmental and sustainability benefits were not adequately addressed. Further, it was posited that future researchers should incorporate elements of those benefits into the development of their models. The results of this study were used to influence the development of the SD model used in the second study.

The SD model developed in the second paper used the gaps identified in the previous study as model inputs. In considering Missouri's energy infrastructure, it became clear that dependence on coal sourced from Wyoming resulted in environmental and sustainability problems. As Missouri's population continues to grow, so too will the stress placed on the coal supply chain resulting in ever-increasing emissions and subsequent increases in the concentration of carbon dioxide in the atmosphere. To lessen these consequences, a transition from coal to solar microgrid technologies was presented to evaluate the environmental, sustainability, and financial investment required. While the model is subject to its simplified linear relationships, the findings should still be considered useful. Mainly, that the environmental and sustainability benefits might be worthwhile even with the considerable financial investment required. As the model is developed further to account for previously mentioned studies, its utility to both the public and private sector will increase. The SD model developed is useful for those responsible for making decisions that affect millions of lives, but not so for the residential customer or engineering manager tasked with determining if a microgrid is appropriate for their building or small community. To accomplish this, the cost benefit analysis conducted in the third paper was developed.

As cost of solar electricity achieves parity with fossil fuels, the need to conduct cost benefit analyses on specific locations increases considerably. The cost benefit analysis presented evaluated the effectiveness of a solar microgrid in partially fulfilling the energy demand of the Toomey Hall building on the Missouri University of Science and Technology campus. The study presented several key findings that added value to the collective work presented here. First, that procurement of site-specific energy demand data considerably improves the value of the results presented. Second, that there are publicly available tools such as PV Watts to aid residential customers and engineering managers in their decision making at no cost. Third, that appropriate selection of discount factors directly influences the feasibility of implementing a microgrid energy system. This paper demonstrated that it is just as important to conduct a building specific analysis as it is to review the collective effectiveness of on-going research and evaluate systematic benefits of an energy transition project.

The work presented here provides a necessary step forward in the process of developing clean energy strategies for the state of Missouri. While one location, be it a state or a residential customer, might serve as a proxy for another it is inappropriate to cite the results presented her as sole justification for microgrid installment. Instead, the methodologies presented should be used with location-specific modifications to produce useful results. Through continued research, systematic studies, and residential customer buy-in microgrids will only improve their effectiveness in transitioning the energy infrastructure away from fossil fuel dependency and succeed in developing a clean energy society.

APPENDIX A.

SYSTEM DYNAMICS MODEL EQUATIONS

Population Subsystem	
Variable	**Denoted By**
Total Population	P
Births	B
Birth Rate	r_b
Deaths	D
Death Rate	r_d
Equations	
$P = B - D$	
$B = P \times r_b$	
$D = P \times r_d$	

Household Population and Energy Demand Subsystem	
Variable	**Denoted By**
Household Specific Population, i	P_i
Initial Household Specific Population Share, i	$P_{i,0}$
Total Population	P
Rate of Change for household population, i	$r_{c,i}$
Total Electricity Demand	D_t
Demand per resident in household population, i	D_i
Equations	
$P_i = P \times (P_{i,0} + r_c)$	
$D_t = \sum_{i=1}^{n} P_i \times D_i$	

Electricity Demand Fulfillment Subsystem	
Variable	**Denoted By**
Coal Production	P_c
Initial Coal Share of Portfolio	$P_{c,0}$
Total Energy Demand	D_t
Renewable Generation	R_g
Initial Renewable Share of Portfolio	$R_{g,0}$
Rate of Renewable Installation	r_i
Equations	
$P_c = (P_{c,0} \times D_t) - (r_i \times D_t)$	
$R_g = (R_{g,0} \times D_t) + (r_i \times D_t)$	

Coal Supply Chain and Fugitive Emissions Subsystem	
Variable	**Denoted By**
Total Emissions	E_t
Mining Process Emissions	E_m
Selection and Washing Emissions	E_{sw}
Transportation Emissions	E_t
Consumption Emissions	E_c
Fugitive Emissions	E_f
Coalbed Carbon Leak Emissions	E_{cl}
Energy Consumption Emissions	E_{ec}
Electricity Production Emissions	E_{ep}
Coal Production	P_c
Emission Factor	EF
Transfer Factor	TF
Global Warming Potential	GWP
Combusted Fossil Fuel Equivalent, Mining Equipment	c_{ff}
Net Heating Value	NHV

Carbon Content	cc
Oxidation Ratio	or
Carbon to Carbon Dioxide Ratio	r_c
Electricity Production Fossil Fuel Equivalent	C_c
Emission Coefficient	L
Combusted Fossil Fuel Equivalent, Selection and Washing Process	$c_{ff,sw}$
Spontaneous Rate of Loss	r_L
Proportion of Transportation Method, i	p_i
Average Length of Transportation Method, i	l_i
Fuel Consumption of Transportation Method, i	f_{ci}
Net Heating Value for fuel used in Transportation Method, i	NHV_i
Carbon Content of Diesel Fuel Used by Transportation Method, i	cc_i
Oxidation Ratio of Diesel Fuel Used by Transportation Method, i	or_i
Fugitive Emission Factor	EF_f
Renewable Generation	R_g
Equations	
$E_t = E_m + E_{sw} + E_t + E_c + E_f$	
$E_m = E_{cl} + E_{ec} + E_{ep}$	
$E_{cl} = P_c \times EF \times TF \times GWP$	
$E_{ec} = c_{ff} \times NHV \times cc \times or \times r_c$	
$E_{ep} = C_c \times P_c \times L$	
$E_{ec,sw} = c_{ff,sw} \times NHV \times cc \times or \times r_c$	
$E_{ep,sw} = C_c \times P_c \times L \times r_L$	
$E_t = \sum_{i=1}^{n} P_c \times p_i \times l_i \times f_{ci} \times NHV_i \times cc_i \times or_i$	
$E_c = P_c \times L$	
$E_f = R_g \times EF_f$	

Total Cost Subsystem	
Variable	**Denoted By**
Total Cost	C_t
Cost of Renewable Installation	C_r
Total Energy Demand	D_t
Rate of Installation	r_i
Initial Renewable Share of Portfolio	$R_{g,0}$
Cost of Delivered Coal	C_c
Initial Coal Share of Portfolio	$P_{c,0}$
Equations	
$C_t = C_r \times D_t \times (r_i - R_{g,0}) - C_c \times D_t \times (P_{c,0} - r_i)$	

APPENDIX B.

SD INITIAL VALUES, UNITS, AND SOURCES

Variable	Type	Initial Value	Units	Source
Population	Stock	6.11 Million	people	60
Births	Flow	-	people	71
Birth Rate	Auxiliary	12.3	per 1000 people	71
Deaths	Flow	-	people	71
Death Rate	Auxiliary	9.4	per 1000 people	71
Single Person Housing Population	Stock	11.35% x (Population)	people	60
Two Person Housing Population	Stock	28.03% x (Population)	people	60
Three Person Housing Population	Stock	18.86 x (Population)	people	60
Four or More Person Housing Population	Stock	41.75% x (Population)	people	60
Rate of Increase 1	Flow	2.08% over 30 years	%/year	Appendix C
Rate of Increase 2	Flow	5.67% over 30 years	%/year	Appendix C
Rate of Decrease 3	Flow	0.73% over 30 years	%/year	Appendix C
Rate of Decrease 4+	Flow	2.14% over 30 years	%/year	Appendix C
Electricity Demand	Auxiliary	-	kWh	-
Coal Production	Stock	81% of Electricity Demand		61
Rate of Decomissioning	Flow	13%/number of years	%/year	-
Renewable Generation	Stock	2% of Electricity Demand		61
Rate of Installation	Flow	13%/number of years	%/year	-
Total Emissions	Auxiliary	-	kg of CO2	74
Emissions from Mining	Auxiliary	-	kg of CO2	74
Emissions from Selection and Washing (SW)	Auxiliary	-	kg of CO2	74
Emissions from Transportation	Auxiliary	-	kg of CO2	74
Emissions from Consumption	Auxiliary	-	kg of CO2	74
Fugitive Emissions	Auxiliary	88	g/kWh	75
Emission Factor	Auxiliary	1.2	m^3/ton	73, 74
Transfer Factor (Density)	Auxiliary	1.98	kg/m^3	-
Global Warming Potential	Auxiliary	1	unitless	74
Combusted Fossil Fuel to Produce 1 kg of Coal	Auxiliary	27.2	kwh/kg	74
Net Heating Value	Auxiliary	20908	kJ/kg	74
Carbon Content	Auxiliary	25.8	kg/GJ	74
Oxidation Ratio	Auxiliary	1	%	74
Conversion Ratio (C -> CO2)	Auxiliary	(44/12)	unitless	74
Coal Equivalent to Run Machinery	Auxiliary	33.7	kg/kWh	74
Emission Coefficient	Auxiliary	840.1914	g CO2/kWh	74
Combusted Fuel for Selection and Washing	Auxiliary	27.2	kg/kWh	74
Coal Equivalent to Run Machinery SW	Auxiliary	3	kWh/kg	74
Spontaenous Rate of Loss	Auxiliary	1	%	74
Transport Proportion	Auxiliary	100	%	62
Average Length of Transport	Auxiliary	1100	km	77
Net Heating Value for Transport Type	Auxiliary	42652	kJ/kg	74
Carbon Content of Transport Fuel	Auxiliary	20.2	kg/GJ	74
Oxidation Ratio of Transport Fuel	Auxiliary	100	%	74
Cost of Delivered Microgrid Electricity	Auxiliary	1800	$/kWh	Paper 3
Cost of Delivered Coal	Auxiliary	42.58	$/ton	63

APPENDIX C.

HOLT’S FORECASTING ANALYSIS TABLES

Year	All households	Population (MAPE = 0.41%)	1 (MAPE = 1.96%)	% Share
2017	126224	310396	35252	0.113571051
2018	127688.0604	313185.5499	36021.12994	0.1150153
2019	128721.9001	314778.7655	36444.13024	0.115776965
2020	129755.7398	316371.981	36867.13054	0.11653096
2021	130789.5795	317965.1966	37290.13083	0.117277398
2022	131823.4192	319558.4121	37713.13113	0.118016393
2023	132857.2589	321151.6277	38136.13143	0.118748056
2024	133891.0986	322744.8433	38559.13173	0.119472495
2025	134924.9383	324338.0588	38982.13203	0.120189817
2026	135958.778	325931.2744	39405.13233	0.120900127
2027	136992.6176	327524.4899	39828.13263	0.121603525
2028	138026.4573	329117.7055	40251.13293	0.122300114
2029	139060.297	330710.921	40674.13323	0.122989991
2030	140094.1367	332304.1366	41097.13352	0.123673253
2031	141127.9763	333897.3521	41520.13382	0.124349994
2032	142161.816	335490.5677	41943.13412	0.125020308
2033	143195.6556	337083.7833	42366.13442	0.125684285
2034	144229.4953	338676.9988	42789.13472	0.126342016
2035	145263.3349	340270.2144	43212.13502	0.126993587
2036	146297.1746	341863.4299	43635.13532	0.127639085
2037	147331.0142	343456.6455	44058.13562	0.128278594
2038	148364.8538	345049.861	44481.13592	0.128912198
2039	149398.6935	346643.0766	44904.13621	0.129539977
2040	150432.5331	348236.2921	45327.13651	0.130162012
2041	151466.3727	349829.5077	45750.13681	0.130778381
2042	152500.2123	351422.7233	46173.13711	0.131389162
2043	153534.0519	353015.9388	46596.13741	0.131994429
2044	154567.8915	354609.1544	47019.13771	0.132594258
2045	155601.7312	356202.3699	47442.13801	0.133188721
2046	156635.5708	357795.5855	47865.13831	0.13377789
2047	157669.4104	359388.801	48288.13861	0.134361835
% Change			2.08%	

Year	All households	Population (MAPE = 0.41%)	2 (MAPE = 0.89%)	% Share
2017	126224	310396	43509	0.280345108
2018	127688.0604	313185.5499	43890.69619	0.280285576
2019	128721.9001	314778.7655	44465.60743	0.28251974
2020	129755.7398	316371.981	45040.51867	0.284731401
2021	130789.5795	317965.1966	45615.42991	0.286920898
2022	131823.4192	319558.4121	46190.34115	0.289088563
2023	132857.2589	321151.6277	46765.25239	0.291234721
2024	133891.0986	322744.8433	47340.16363	0.29335969
2025	134924.9383	324338.0588	47915.07487	0.295463783
2026	135958.778	325931.2744	48489.98611	0.297547305
2027	136992.6176	327524.4899	49064.89735	0.299610557
2028	138026.4573	329117.7055	49639.80859	0.301653832
2029	139060.297	330710.921	50214.71983	0.303677421
2030	140094.1367	332304.1366	50789.63107	0.305681606
2031	141127.9763	333897.3521	51364.54231	0.307666664
2032	142161.816	335490.5677	51939.45355	0.309632869
2033	143195.6556	337083.7833	52514.36479	0.311580488
2034	144229.4953	338676.9988	53089.27603	0.313509782
2035	145263.3349	340270.2144	53664.18727	0.31542101
2036	146297.1746	341863.4299	54239.09851	0.317314423
2037	147331.0142	343456.6455	54814.00975	0.31919027
2038	148364.8538	345049.861	55388.92099	0.321048795
2039	149398.6935	346643.0766	55963.83223	0.322890235
2040	150432.5331	348236.2921	56538.74347	0.324714826
2041	151466.3727	349829.5077	57113.65471	0.326522797
2042	152500.2123	351422.7233	57688.56595	0.328314375
2043	153534.0519	353015.9388	58263.47719	0.330089782
2044	154567.8915	354609.1544	58838.38843	0.331849236
2045	155601.7312	356202.3699	59413.29967	0.33359295
2046	156635.5708	357795.5855	59988.21091	0.335321135
2047	157669.4104	359388.801	60563.12215	0.337033998
% Change			5.67%	

Year	All households	Population (MAPE = 0.41%)	3 (MAPE = 1.46%)	% Share
2017	126224	310396	19509	0.188555909
2018	127688.0604	313185.5499	19611.11265	0.187854574
2019	128721.9001	314778.7655	19683.79764	0.187596494
2020	129755.7398	316371.981	19756.48263	0.187341015
2021	130789.5795	317965.1966	19829.16762	0.187088095
2022	131823.4192	319558.4121	19901.85261	0.186837697
2023	132857.2589	321151.6277	19974.5376	0.186589784
2024	133891.0986	322744.8433	20047.22259	0.186344318
2025	134924.9383	324338.0588	20119.90758	0.186101264
2026	135958.778	325931.2744	20192.59256	0.185860586
2027	136992.6176	327524.4899	20265.27755	0.18562225
2028	138026.4573	329117.7055	20337.96254	0.185386221
2029	139060.297	330710.921	20410.64753	0.185152466
2030	140094.1367	332304.1366	20483.33252	0.184920953
2031	141127.9763	333897.3521	20556.01751	0.184691649
2032	142161.816	335490.5677	20628.7025	0.184464523
2033	143195.6556	337083.7833	20701.38749	0.184239544
2034	144229.4953	338676.9988	20774.07248	0.184016682
2035	145263.3349	340270.2144	20846.75746	0.183795906
2036	146297.1746	341863.4299	20919.44245	0.183577189
2037	147331.0142	343456.6455	20992.12744	0.1833605
2038	148364.8538	345049.861	21064.81243	0.183145813
2039	149398.6935	346643.0766	21137.49742	0.182933099
2040	150432.5331	348236.2921	21210.18241	0.182722332
2041	151466.3727	349829.5077	21282.8674	0.182513484
2042	152500.2123	351422.7233	21355.55239	0.18230653
2043	153534.0519	353015.9388	21428.23737	0.182101444
2044	154567.8915	354609.1544	21500.92236	0.181898201
2045	155601.7312	356202.3699	21573.60735	0.181696776
2046	156635.5708	357795.5855	21646.29234	0.181497144
2047	157669.4104	359388.801	21718.97733	0.181299283
% Change			-0.73%	

Year	All households	Population (MAPE = 0.41%)	4 (MAPE = 1.21%)	% Share
2017	126224	310396	16212	0.208920218
2018	127688.0604	313185.5499	16310.48252	0.208317178
2019	128721.9001	314778.7655	16302.23944	0.207158058
2020	129755.7398	316371.981	16293.99636	0.206010612
2021	130789.5795	317965.1966	16285.75328	0.204874665
2022	131823.4192	319558.4121	16277.5102	0.203750045
2023	132857.2589	321151.6277	16269.26712	0.202636583
2024	133891.0986	322744.8433	16261.02404	0.201534114
2025	134924.9383	324338.0588	16252.78096	0.200442477
2026	135958.778	325931.2744	16244.53788	0.199361512
2027	136992.6176	327524.4899	16236.29481	0.198291063
2028	138026.4573	329117.7055	16228.05173	0.197230978
2029	139060.297	330710.921	16219.80865	0.196181107
2030	140094.1367	332304.1366	16211.56557	0.195141303
2031	141127.9763	333897.3521	16203.32249	0.194111422
2032	142161.816	335490.5677	16195.07941	0.193091323
2033	143195.6556	337083.7833	16186.83633	0.192080867
2034	144229.4953	338676.9988	16178.59325	0.191079918
2035	145263.3349	340270.2144	16170.35018	0.190088341
2036	146297.1746	341863.4299	16162.1071	0.189106008
2037	147331.0142	343456.6455	16153.86402	0.188132787
2038	148364.8538	345049.861	16145.62094	0.187168555
2039	149398.6935	346643.0766	16137.37786	0.186213185
2040	150432.5331	348236.2921	16129.13478	0.185266558
2041	151466.3727	349829.5077	16120.8917	0.184328553
2042	152500.2123	351422.7233	16112.64862	0.183399053
2043	153534.0519	353015.9388	16104.40554	0.182477942
2044	154567.8915	354609.1544	16096.16247	0.181565109
2045	155601.7312	356202.3699	16087.91939	0.180660442
2046	156635.5708	357795.5855	16079.67631	0.179763831
2047	157669.4104	359388.801	16071.43323	0.17887517
% Change			-3.00%	

Year	All households	Population (MAPE = 0.41%)	5 (MAPE = 1.53%)	% Share
2017	126224	310396	7319	0.117897782
2018	127688.0604	313185.5499	7425.96022	0.118555282
2019	128721.9001	314778.7655	7405.522454	0.117630591
2020	129755.7398	316371.981	7385.084688	0.116715214
2021	130789.5795	317965.1966	7364.646922	0.11580901
2022	131823.4192	319558.4121	7344.209156	0.114911842
2023	132857.2589	321151.6277	7323.77139	0.114023576
2024	133891.0986	322744.8433	7303.333624	0.113144079
2025	134924.9383	324338.0588	7282.895858	0.112273223
2026	135958.778	325931.2744	7262.458092	0.111410881
2027	136992.6176	327524.4899	7242.020326	0.110556929
2028	138026.4573	329117.7055	7221.58256	0.109711244
2029	139060.297	330710.921	7201.144794	0.108873707
2030	140094.1367	332304.1366	7180.707028	0.108044202
2031	141127.9763	333897.3521	7160.269262	0.107222612
2032	142161.816	335490.5677	7139.831496	0.106408826
2033	143195.6556	337083.7833	7119.39373	0.105602733
2034	144229.4953	338676.9988	7098.955963	0.104804223
2035	145263.3349	340270.2144	7078.518197	0.104013192
2036	146297.1746	341863.4299	7058.080431	0.103229533
2037	147331.0142	343456.6455	7037.642665	0.102453144
2038	148364.8538	345049.861	7017.204899	0.101683926
2039	149398.6935	346643.0766	6996.767133	0.100921778
2040	150432.5331	348236.2921	6976.329367	0.100166604
2041	151466.3727	349829.5077	6955.891601	0.099418309
2042	152500.2123	351422.7233	6935.453835	0.098676798
2043	153534.0519	353015.9388	6915.016069	0.097941981
2044	154567.8915	354609.1544	6894.578303	0.097213766
2045	155601.7312	356202.3699	6874.140537	0.096492066
2046	156635.5708	357795.5855	6853.702771	0.095776793
2047	157669.4104	359388.801	6833.265005	0.095067862
% Change			-2.28%	

Year	All households	Population (MAPE = 0.41%)	6 (MAPE = 3.09%)	% Share
2017	126224	310396	2798	0.054085749
2018	127688.0604	313185.5499	2816.045716	0.053949725
2019	128721.9001	314778.7655	2822.011529	0.053790379
2020	129755.7398	316371.981	2827.977342	0.053632638
2021	130789.5795	317965.1966	2833.943154	0.053476478
2022	131823.4192	319558.4121	2839.908967	0.053321875
2023	132857.2589	321151.6277	2845.87478	0.053168806
2024	133891.0986	322744.8433	2851.840593	0.053017249
2025	134924.9383	324338.0588	2857.806406	0.05286718
2026	135958.778	325931.2744	2863.772219	0.052718578
2027	136992.6176	327524.4899	2869.738031	0.052571422
2028	138026.4573	329117.7055	2875.703844	0.052425691
2029	139060.297	330710.921	2881.669657	0.052281364
2030	140094.1367	332304.1366	2887.63547	0.052138421
2031	141127.9763	333897.3521	2893.601283	0.051996842
2032	142161.816	335490.5677	2899.567096	0.051856607
2033	143195.6556	337083.7833	2905.532909	0.051717698
2034	144229.4953	338676.9988	2911.498721	0.051580097
2035	145263.3349	340270.2144	2917.464534	0.051443783
2036	146297.1746	341863.4299	2923.430347	0.051308741
2037	147331.0142	343456.6455	2929.39616	0.051174951
2038	148364.8538	345049.861	2935.361973	0.051042397
2039	149398.6935	346643.0766	2941.327786	0.050911061
2040	150432.5331	348236.2921	2947.293598	0.050780927
2041	151466.3727	349829.5077	2953.259411	0.050651978
2042	152500.2123	351422.7233	2959.225224	0.050524198
2043	153534.0519	353015.9388	2965.191037	0.050397572
2044	154567.8915	354609.1544	2971.15685	0.050272084
2045	155601.7312	356202.3699	2977.122663	0.050147718
2046	156635.5708	357795.5855	2983.088475	0.05002446
2047	157669.4104	359388.801	2989.054288	0.049902294
% Change			-0.42%	

Year	All households	Population (MAPE = 0.41%)	7 (MAPE = 5.73%)	% Share
2017	126224	310396	1624	0.036624183
2018	127688.0604	313185.5499	1611.66917	0.036022365
2019	128721.9001	314778.7655	1597.626896	0.035527772
2020	129755.7398	316371.981	1583.584621	0.035038161
2021	130789.5795	317965.1966	1569.542347	0.034553456
2022	131823.4192	319558.4121	1555.500072	0.034073584
2023	132857.2589	321151.6277	1541.457798	0.033598474
2024	133891.0986	322744.8433	1527.415523	0.033128054
2025	134924.9383	324338.0588	1513.373248	0.032662256
2026	135958.778	325931.2744	1499.330974	0.032201012
2027	136992.6176	327524.4899	1485.288699	0.031744255
2028	138026.4573	329117.7055	1471.246425	0.03129192
2029	139060.297	330710.921	1457.20415	0.030843944
2030	140094.1367	332304.1366	1443.161876	0.030400263
2031	141127.9763	333897.3521	1429.119601	0.029960816
2032	142161.816	335490.5677	1415.077327	0.029525543
2033	143195.6556	337083.7833	1401.035052	0.029094385
2034	144229.4953	338676.9988	1386.992778	0.028667283
2035	145263.3349	340270.2144	1372.950503	0.028244181
2036	146297.1746	341863.4299	1358.908229	0.027825022
2037	147331.0142	343456.6455	1344.865954	0.027409753
2038	148364.8538	345049.861	1330.82368	0.026998318
2039	149398.6935	346643.0766	1316.781405	0.026590665
2040	150432.5331	348236.2921	1302.739131	0.026186742
2041	151466.3727	349829.5077	1288.696856	0.025786498
2042	152500.2123	351422.7233	1274.654582	0.025389884
2043	153534.0519	353015.9388	1260.612307	0.024996849
2044	154567.8915	354609.1544	1246.570033	0.024607346
2045	155601.7312	356202.3699	1232.527758	0.024221328
2046	156635.5708	357795.5855	1218.485484	0.023838747
2047	157669.4104	359388.801	1204.443209	0.023459558
% Change			-1.32%	

Year	All households	Population (MAPE = 0.41%)	4 or more (%)
2017	126224	310396	0.417527932
2018	127688.0604	313185.5499	0.41684455
2019	128721.9001	314778.7655	0.414106801
2020	129755.7398	316371.981	0.411396625
2021	130789.5795	317965.1966	0.408713609
2022	131823.4192	319558.4121	0.406057347
2023	132857.2589	321151.6277	0.403427439
2024	133891.0986	322744.8433	0.400823496
2025	134924.9383	324338.0588	0.398245136
2026	135958.778	325931.2744	0.395691983
2027	136992.6176	327524.4899	0.393163668
2028	138026.4573	329117.7055	0.390659833
2029	139060.297	330710.921	0.388180122
2030	140094.1367	332304.1366	0.385724188
2031	141127.9763	333897.3521	0.383291692
2032	142161.816	335490.5677	0.3808823
2033	143195.6556	337083.7833	0.378495683
2034	144229.4953	338676.9988	0.376131521
2035	145263.3349	340270.2144	0.373789497
2036	146297.1746	341863.4299	0.371469304
2037	147331.0142	343456.6455	0.369170635
2038	148364.8538	345049.861	0.366893195
2039	149398.6935	346643.0766	0.364636689
2040	150432.5331	348236.2921	0.36240083
2041	151466.3727	349829.5077	0.360185337
2042	152500.2123	351422.7233	0.357989933
2043	153534.0519	353015.9388	0.355814345
2044	154567.8915	354609.1544	0.353658306
2045	155601.7312	356202.3699	0.351521554
2046	156635.5708	357795.5855	0.349403831
2047	157669.4104	359388.801	0.347304885
% Change			-2.44%

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