Energy Technology Allocation for Distributed Energy Resources: A Technology-Policy Framework

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Abstract of the Dissertation

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Distributed energy resources (DER) are emerging rapidly. New engineering technologies, materials, and designs improve the performance and extend the range of locations for DER. In contrast, constructing new or modernizing existing high voltage transmission lines for centralized generation are expensive and challenging. In addition, customer demand for reliability has increased and concerns about climate change have created a pull for swift renewable energy penetration. In this context, DER policy makers, developers, and users are interested in determining which energy technologies to use to accommodate different end-use energy demands.

We present a two-stage multi-objective strategic technology-policy framework for determining the optimal energy technology allocation for DER. The framework simultaneously considers economic, technical, and environmental objectives. The first stage utilizes a Data Envelopment

Analysis model for each end-use to evaluate the performance of each energy technology based on the three objectives. The second stage incorporates factor efficiencies determined in the first stage, capacity limitations, dispatchability, and renewable penetration for each technology, and demand for each end-use into a bottleneck multi-criteria decision model which provides the Pareto-optimal energy resource allocation. We conduct several case studies to understand the roles of various distributed energy technologies in different scenarios. We construct some policy implications based on the model results of set of case studies.

I dedicate this dissertation to my mentors, committee members, fiancé, the Department of Technology and Society, family, and friends.

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List of Abbreviations

BTU: British Thermal Unit

C: Carbon

CAOP: Canon One Park

CCHP: Combined Cooling, Heating, and Power

CHP: Combined Heating and Power

CRS: Constant Returns to Scale

DEA: Data Envelopment Analysis

DER: Distributed Energy Resources

DER-CAM: Distributed Energy Resources-Customer Adaption Model

EM: Emissions

EPA: Environmental Protection Agency

EUI: Energy Usage Intensity

G: Gram

GHG: Green House Gases

GP: Goal Programming

HVAC: Heating, Ventilation, and Air Conditioning

KG: Kilogram

KWH: Kilowatt Hour

LC: Levelized Cost

LIMH: Long Island Marriot Hotel

M: Big M Value

MW: Megawatt

N: Nitrogen

NETL: National Energy Technology Laboratory

NREL: National Renewable Energy Laboratory

O&M: Operations and Maintenance

OPF: Optimal Power Flow

PV: Photovoltaic

RF: Reliability Factor

S: Sulfur

SB: Stony Brook University

SBMC: Stony Brook Medical Center

SF: Stanford University

SHSM: Smith Haven Shopping Mall

UI: University of Iowa

UT: University of Texas

VRS: Variable Returns to Scale

Chapter 1

Introduction

Distributed energy resources (DER) consist of small-scale energy generation and energy storage units located at or near the load site. DER can be operated in a controlled, coordinated way either while connected to the central electricity grid or in an islanded mode to supply energy to consumers [1] [2]. DER are typically less than 30MW in power capacity [3] [4]. However, this is not consistent in the literature. Cardell and Tabors [5] define that DER have a power capacity up to 1MW, whereas Sharma and Bartels [6] define the capacity up to 100MW. Some noticeable DER examples in the U.S. include: the Transamerica Pyramid building in California, the Cornell campus in New York, and the Food and Drug Administration's research facility in Maryland.

According to the International Energy Agency [7], DER are emerging rapidly for multiple reasons. New engineering technologies, materials, and designs improve the performance and extend the range of locations for DER. Constructing new or modernizing existing high voltage transmission lines for centralized generation are expensive and challenging. Customer demand for reliability has increased. Concerns for climate change have created a pull for swift renewable energy penetration.

DER systems offer many benefits [8] [9]. First, DER systems enable cogeneration[1] and trigeneration[2], and avoid high voltage and long distance transmission losses, thus increasing overall efficiency [10] [11]. Second, DER expand the use of renewable sources and siting is easier as DER avoid the need of new high voltage transmission capacity [12] [13]. Third, DER can be built swiftly and capacity can be added easily based on the incremental demands of energy [14]. Finally, DER systems are capable of providing reliable and sustainable energy to consumers [15] [16].

DER provide a multitude of services to utilities and consumers [17] that include standby or primary generation, storage, peak shaving[3], peak sharing[4], base-load generation[5], combined heating and power (CHP), or combined cooling, heating and power (CCHP) [3] [4]. Additional impetus was added to encourage DER because of climate change, manmade disasters (such as accidents or military attacks), and natural disasters (such as heat waves that increase energy loads or tropical and extra-tropical cyclones that down transmission lines) [18].

There are several energy generation and storage technologies that can be implemented into DER architecture and there are various end-uses that consume energy [19]. As DER adoption grows, a single energy technology such as diesel reciprocating engines and natural gas turbines can be

[1] Cogeneration or combined heat and power (CHP) refers to simultaneously generation of electric and useful thermal energy.
[2] Trigeneration or combined cooling, heat and power (CCHP) refers to the simultaneously generation of electricity and useful thermal energy for heating or cooling.
[3] Peak shaving is the process of avoiding the purchase of energy from a local utility grid during the peak hours due to high energy tariffs.
[4] Peak sharing is the process of distributing energy loads among various energy sources during the peak hours.
[5] Base load generation is the process of supplying a minimum amount of energy constantly at all times.

over utilized by the consumers due to economic advantages [3] [7]. In such cases, the consequences lead to externalities such as pollution and dependence on fossil fuels [20] [21] [16] [22]. Thus, to enhance the system efficiency, rate of return, and ease the environmental impact simultaneously, it is necessary to establish a balanced strategic framework of optimal energy technologies and specific end-use allocation for DER adopters [23].

U.S. energy policy must look at DER energy technology allocation as a sub-system of the overall energy – economic – technical – environmental system rather than as an isolated system for the nation's future energy planning and sustainability [24] [25]. This leads to the research question – *What is an appropriate technology-policy framework that optimally allocates various energy technologies among different end-uses in a distributed energy resources system*? A technology-policy framework for a specific circumstance formulates a set of objectives for desired outcomes in that situation [26]. It will be used to inform decisions and set effective policies regarding the technologies relevant to that situation [26].

To address this question, we develop a two-stage multi-objective strategic framework for determining the optimal energy technology allocation for DER. The framework simultaneously considers economic, technical, and environmental objectives. The framework takes into account the needs of both the DER users and regulators. The proposed framework can be used for DER design decision-making and for the development of DER regulatory policy.

Chapter 2

Background

DER is a disruptive innovation, meaning that DER has potential to change the energy market by applying a different set of values (such as energy efficiency, renewable energy, power quality and reliability) [3] [27]. However, it may offer poor economic justification for early adopters [3] [27]. As commercialization continues, these technologies will be characterized by lower costs and improved performance [28]. Research and development in energy technologies such as solar photovoltaic, fuel cells and wind turbines in particular are dramatically changing the economic calculus in remote locations that lack a supply of cheap gas or where the transmission constraints limit power flows [4]. In addition, increasingly sophisticated automation and controls of the energy management systems allow DER to operate much more cost-effectively than mega-scale utilities [29] [30]. Thus, the DER paradigm becomes more acceptable to users and more economically feasible [31].

As a consequence, extensive research has been done in the context of DER systems planning and management [32]. Researchers in the past have proposed a variety of approaches based on analytical optimization techniques, mathematical programming, evolutionary programming, multi-criteria decision analysis, heuristic models, and genetic algorithms to optimize, design, or operate of DER systems. Researchers such as Pohekar and Ramachandran [33], Figueria et al. [34], Loken [35], Alarcon-Rodriguez et al. [36], Connolly et al. [37], and Fadaee and Radzi [38] review, study, and discuss the literature regarding DER. In particular, Loken [35] concludes that there is no one methodology that is generally better suited than others for energy planning problems. On the whole, these reviews broadly classify the DER systems modeling literature into two categories – single-objective and multi-objective models.

2.1. Single-Objective DER research

Most of the single-objective methods optimize technical parameters such as DER power sizing and siting in particular scenarios [36]. Celli et al. [39] identify which sizes and locations are beneficial for DER system operation. Harrison and Wallace [40] present an Optimal Power Flow (OPF) approach to obtain the maximum DER capacity in predefined locations. Harrison et al. [41] upgrade the OPF to optimize both DER locations and size, using a hybrid genetic algorithm and OPF approach, where the genetic algorithm is used to solve the combinatorial problem, and the OPF solves the capacity allocation problem. Keane and O'Malley [42] explore a similar problem, and propose a linear programming technique to find the maximum capacity that can be installed using a rigid connection. Ooka and Komamura [43] propose an optimal design method that uses a genetic algorithm for managing a building's energy system using the grid electricity and other conventional recourses such as electric or gas heat pumps, boilers, etc. The method provides efficient equipment capacity and operation planning for cooling, heating, and power operations in a large building. More recently, Voll et al. [44] propose a methodology that optimizes the structure and capacities of the DER supply systems such that the optimum operational efficiency is achieved. Ashouri et al. [45] present a design framework for the optimal selection and sizing of a smart building system. Their model uses mixed integer linear programming techniques to compute and compare various configurations and operating strategies for a building's energy system.

Furthermore, researchers such as Kim et al. [46], Wang and Nehrir [47], Wang et al. [48], and Soroudi et al. [49] propose various single-objective approaches to minimize power losses in DER systems. Niknam et al. [50] propose a stochastic model for optimal energy management in a typical grid-connected micro grid. Menon et al. [51] study the optimal design of multi-node micro grids integrating heat pumps and cogeneration units by considering optimal predictive control strategies. Zhou et al. [52] provide a generic energy systems engineering framework for the optimal design of DER systems in a hotel.

In addition, most of the single-objective models in the literature minimize cost parameters of DER systems [53]. For cost minimization single-objective DER planning approaches, cost is mainly examined from three perspectives [36]. The models are formulated either from a DER developer's perspective [54], a DER user's perspective who invests in DER [55] [56], or a DER operator's perspective who tends to minimize the cost of network reinforcements [57]. Wright et al. [58] describe exploratory analysis that examines the economics of on-site generation systems on local electricity networks. Kalantar et al. [59] accomplish optimal sizing and economic analysis of the wind turbine, solar photovoltaic, and battery hybrid system using a genetic algorithm for minimizing the annualized cost of the system. Fumo et al. [60] present a mathematical analysis to demonstrate that CHP systems increase the site energy consumption and therefore fail to yield economical savings.

The optimization of energy systems focusing on economic objectives for designing energy systems in the residential and commercial sectors dominates the majority of the cost optimization research. For instance, Van Schinjndel et al. [61] develop a mathematical model to evaluate the economic benefit of a newly installed DER system at a hospital using simulation and optimization. Cardona et al. [62] use a single-objective linear programming method for energy cost saving at airports. Ziher et al. [63] use a similar approach for analyzing the trigeneration system in a hospital. Arcuri et al. [64] and Casisi et al.[65] propose similar mixed integer programming models to optimize the operating cost for a distributed cogeneration system with a local district heating network. Houwing et al. [66] apply a comprehensive framework to address uncertainties in cost that influence the design and operation of a residential DER system that consists of micro-CHP technologies. Lozano et al. [67] present a mixed integer linear programming model to optimize the cost of combined cooling, heat and power systems with thermal storage for commercial users. Wakui et al. [68] use an optimization approach based on mixed integer linear programming to investigate a suitable operational strategy of solid oxide fuel cell cogeneration systems to save energy costs in a housing complex.

More notably, Ernest Orlando Lawrence Berkeley National Laboratory developed an economic model (known as DER-CAM) for a consumer to adopt DER. The model uses the general algebraic modeling system optimization software to minimize the cost of operating on-site generation [69]. The primary focus of the model is economic [70]. However, Marnay et al.

(2013) imply that DER-CAM can have an objective function focusing on cost, CO_2 emission, or a weighted combination of both [71] [72].

Few researchers primarily focus on the environmental aspects of DER systems [73]. Strachan and Farrell [22] systematically analyze emissions from DER energy technologies and conclude that there is a need for a rigorous regulatory framework for DER CHP technologies. Pehnt [74] investigates the environmental impact of micro cogeneration DER systems by carrying out a detailed life cycle assessment. Allison et al. [75] advocate technology-forcing regulation which would require the reduction of emissions from the DER units. Mancarella et al. [21] formulate a comprehensive emission assessment framework for distributed cogeneration systems. Chicco and Mancarella [76] [77] in their two papers, perform an in-depth assessment of greenhouse gas emissions from cogeneration and trigeneration DER systems. They contend that possible emission reduction benefits in DER systems arise only from the interaction of energy technologies through combined production processes, optimal composition of energy technologies, and the development of new energy generation technologies.

Due to the rise in climate change concerns, the environmental impact from energy systems cannot be ignored [78] [79] [80]. Thus, the DER allocation problem becomes more challenging when attempting to minimize both the cost and environmental impact objectives simultaneously. [81]. DER modeling becomes even more complex when technical objectives such as power quality and reliability are considered as well. The difficulty arises as economic, technical, and environmental objectives often conflict with one another [82] [81].

Based on the previously presented DER literature, the single-objective models usually optimize one objective – generally cost – while treating other objectives as constraints, or the objectives are aggregated into a single-objective function through a weighted sum method that is optimized. The major drawback of the weighted-sum approach is the difficulty of determining appropriate values for the weights [36]. Furthermore, it is imprecise to obtain quantitative weights to evaluate the energy systems based on conflicting objectives such as economic, technical, and environmental functions [81] [43] [39]. In addition, weighted-sum solutions are sensitive to the set of parameters considered and inconsistencies in any of the specified weights will lead to biased and sometimes misleading results [36]. For this reason, few researchers aggregate various attributes into a single monetary parameter; this approach lacks accuracy and does not capture the true nature of multi-objective optimization [83]. While exemplifying cases, Alarcon et al. [36] state that when attributes cannot be converted to cost accurately or when a larger number of objectives are analyzed, a multi-objective approach becomes essential.

2.2. Multi-Objective DER research

Haesen et al. [82] discuss the drawbacks of single-objective formulations and identify the advantages of multi-objective approaches. Celli et al. [84] contend that multi-objective approaches allow a better simulation of reality and assist the decision-making process. Moreover, multi-objective DER planning methods provide valuable information about the correlations between the benefits and impacts of DER systems [84]. From a high-level standpoint, a multi-objective analysis of DER planning can provide an insight about incentives and policies to encourage DER developments such that the benefits and impacts are balanced [36]. However in the DER literature, in most of the multi-objective models, the objectives are either weighted into a single objective or each objective is solved separately and one solution is chosen.

Heretofore, in multi-objective approaches, objectives are formulated from the DER users' or the operators' perspectives [85]. Researchers employed multi-objective techniques to optimize various aspects of DER systems. DER multi-objective models are broadly used for three purposes– 1) economic planning and operation optimization for a single DER technology, 2) technical design of DER power systems from both utility and DER operator standpoints, and 3) environmental impact optimization of DER systems.

Most of the multi-objective research primarily focuses on economics while considering other attributes. Tsay [86] presents a multi-objective approach based on evolutionary programming to solve the economical operation problem of cogeneration systems under emission constraints. Celli et al. [39] present a multi-objective technique to minimize different costs of embedded generation in distributed networks. They investigate the cost of network upgradation, cost of power losses, cost of energy not supplied, and cost of power quality. Aki et al. [87] use a multi-objective model of cost reduction and CO_2 emission mitigation of fuel cells. Wang et al. [48] employ a genetic multi-objective algorithm to assist designers in green building design while considering both economical and environmental criteria. Zangeneh and Jadid [88] present a multi-objective optimization approach to generate a Pareto set of DER unit locations and sizes by minimizing three cost functions – total cost of installation and operation, cost of energy losses, and cost of energy not served. Ghopal and Khan [89] implement a multi-objective optimization procedure to find optimal design values by minimizing two objective functions – energy cost and material cost.

More recently, Celli at al. [90] propose a multi-objective genetic algorithm that simultaneously considers cost and CO_2 emission to solve the optimal placement of different types of DER. Mavrotas et al. [91] present an integrated modeling and optimization framework to minimize cost and maximize demand satisfaction for the CHP system planning in large service sector consumers. Sayyaadi et al. [92] present an economic model to minimize the total levelized cost of a DER system. The objective functions are based on thermodynamic and thermoeconomic analysis. Gebreslassie et al. [93] propose a multi-objective formulation that accounts for minimizing cost and environmental impact at the DER design stage. Sayyaadi [94] performs a multi-objective optimization for designing a benchmark cogeneration system by considering economic, exergetic, and environmental criteria. Kavvadias and Maroulis [95] develop a multi-objective optimization method for the design of trigeneration plants based on economic, energetic, and environmental criteria. Ren et al. [81] develop a multi-objective linear optimization model to determine the optimal operating strategy of a district DER system while combining the pure minimization of energy cost with the pure minimization of CO_2 emissions. They perform a tradeoff analysis between the independent environmental and economic optimizations. Soroudi et al. [49] present a long-term two-stage heuristic planning model for distributed energy network expansion. The multi-objective model determines the optimal schemes of investments, sizing, and placement of DER over the planning period. Similarly, Carvalho et al. [96] apply a multi-objective mixed integer linear programming model to a DER trigeneration system. They consider annual cost and CO_2 emissions to obtain a set of solutions presenting optimal tradeoffs between the economic and environmental objectives.

Much of the multi-objective research primarily focuses on technical and design aspects of DER technologies or systems along with other functions. Haesen et al. [82] propose a multi-objective evolutionary algorithm to optimize the long-term planning of DER placement, sizing, and tradeoffs. They use bi-objective plots to examine correlations or conflicts between multiple objectives. Haesen et al. [97] use iterative mixed integer quadratic programming for planning time-variant DER. The authors identify that some objectives such as voltage sags and losses cannot be formulated as a mathematical function of DER type, location, and size. Harrison et al. [98] develop a multi-objective Optimal Power Flow model and combine it with genetic algorithms to maximize the DER capacity in existing and future networks. They also simulate and identify compromise solutions that would benefit all DER stakeholders. Harrison et al. [99] state that DER capacity maximization will produce an increase in line losses, and cost minimization of network investments conflicts with capacity maximization and line loss minimization. Becerra-López and Golding [100] promote a multi-objective model to optimize capacity expansion of regional power generation systems. Tang and Tang [101] use Analytical Hierarchy Process (AHP) [102] to perform a weighted-sum of four objectives (investment cost, energy losses, voltage quality, and supply reliability) to optimize DER locations and sizes. Alarcon-Rodriguez et al. [103] present a flexible multi-objective planning framework for the integration of stochastic and controllable DER in the distribution grid. Later, this was extended by Haesen et al. [104] to compare network reinforcement of DER systems as an alternative planning option. They also examine the effects of different energy tariff schemes.

Recently, Abdollahi and Meratizaman [105] perform a multi-objective genetic algorithm optimization for designing a distributed CCHP system and find a set of Pareto-optimal solutions. Rubio-Maya et al. [106] develop a nonlinear design optimization model for the selection and sizing of energy technologies in a poly-generation design. Fazlollahi et al. [107] explain an energy system optimization model that optimizes the configuration and the operating conditions of an energy system and parametrically optimize CO_2 emissions as a second objective function. Later, Fazlollahi et al. [108] present a multi-objective optimization model for the sizing and operation optimization of district heating systems with heat storage tanks. The model includes process design and energy integration techniques for optimizing the temperature intervals, the volume, and the operation strategy of thermal storage tanks.

Society's desire for less polluting energy sources conflicts with the users' inclination towards an affordable and reliable energy supply. Few researchers principally focus on environmental aspects of DER systems along with other functions. Pelet et al. [109] use a multi-objective evolutionary algorithm to study the optimization of the design parameters of an integrated energy system for a remote community. They argue that separating and ranking the two objectives (total cost and CO_2 emissions) enables more informed design decisions. Furthermore, they recognize the conflict between cost and environmental benefits and conclude that clean energy technologies are more expensive. Alarcon-Rodriguez et al. [110] propose a multi-criteria evaluation technique to explicitly formulate an environmental objective along with a flexible treatment of other relevant constraints. Moura et al. [111] propose a multi-objective method to maximize the renewable energy contribution to the peak load, while minimizing the combined intermittence, at minimum cost. Their model considers the contribution of the large-scale demand-side management and demand response technologies. Fesanghary et al. [112] present a multi-objective optimization model based on the harmonic search algorithm to design low-emissions and energy-efficient residential buildings with DER systems.

2.3. Remarks on DER research

Through the widespread literature search, we draw some implications about DER systems modeling research. It is evident that nearly all of DER systems modeling research (except [69]) originates from European and Asian nations and do not explicitly deal with the U.S. energy policy. No research investigates a wide range of energy technologies simultaneously –

conventional (e.g. engines, boilers), new (e.g. different types of fuel cells, geothermal pumps), renewable (e.g. solar, wind), storage (e.g. batteries, pumped storage), CHP, and CCHP. The competitiveness and selection of DER energy technologies is not examined by developing a technology-policy framework. DER system planning and modeling is mostly done from a user or operator perspective. DER system planning is not formulated with respect to specific energy end-use demands of a consumer and the allowable controllability of those demands. A small number of researchers study economic, technical, and environmental aspects together. However, they handle them either by weighting, aggregating into a single parameter, or solving independently and analyzing a tradeoff relation among them.

This research fills this gap by introducing an innovative school of thought that aims to find a Pareto-optimal energy resource to end-use allocation in a DER system. We develop a hybrid multi-objective two-stage DER technology-policy framework. Unlike previous models, this model considers economic, technical, and environmental objectives simultaneously without the need of weights and thus eliminates the subjectivity that would otherwise arise.

In addition, the model is useful to understand the competiveness of different energy technologies in optimally supplying energy to particular end-uses. Furthermore, the model regards controllable or sheddable loads[6] for various end-uses by considering the minimum power dispatchability required for particular energy end-uses. On the whole, the proposed framework can be useful for DER design decision-making, for the development of DER regulatory policy, and for the determination of incentives and taxes to promote or oppose certain DER technologies for the welfare of both users and society.

[6] Load shedding is the process of disconnecting the energy supply to certain uses when the energy demand becomes higher than the supply capacity.

Chapter 3

DER Technology-Policy Framework

There are several types of DER technologies available ranging from conventional combustion engines to advanced fuel cells. DER technologies are capable of performing different tasks such as generating, supplying, and storing electric energy, thermal energy, or a combination of both (CHP and CCHP). El-Khattam et al. [113] and Chicco and Mancarella [114] provide detailed reviews of DER technologies and outline possible structures, characteristics, components, energy flows, and interactions of DER systems. On the other hand, there are various energy end-uses of a consumer that demand energy. Figure 1 shows a possible DER architecture with various fuels, energy technologies, and end-uses.

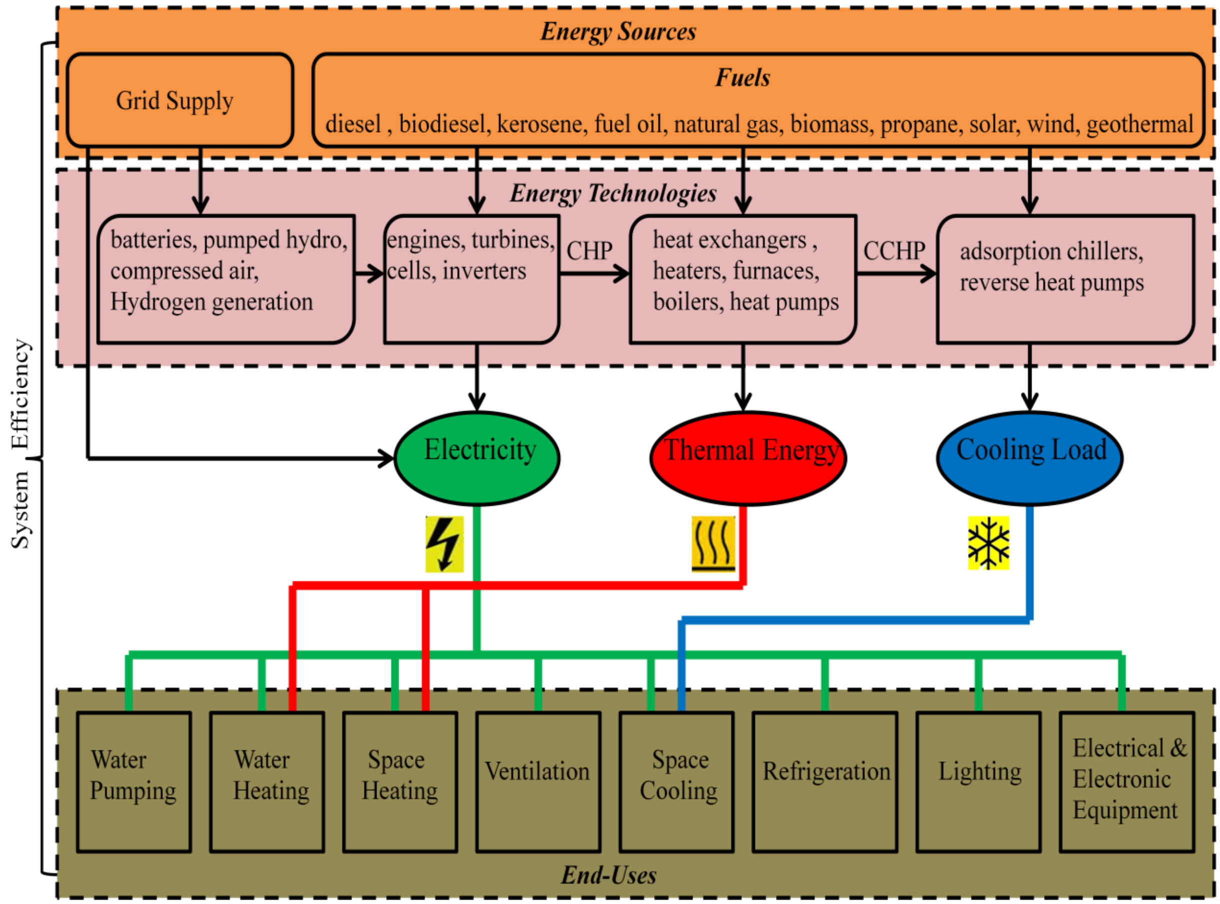


Figure 1. Fuels, energy technologies, end-uses

3.1. Rationale

Every unit (kWh) of energy transfer from each energy technology resource to an end-use has a corresponding system efficiency [115]. The system efficiency is a combination of fuel to output efficiency (or energy technology efficiency) of an energy resource and end-use device efficiency [116]. Tables 1 and 2 tabulate all energy technology efficiencies and end-use devices efficiencies, respectively. A dash implies that the related energy technology does not produce that energy form. For example, a gas heater does not produce electrical energy and hence there is no corresponding effective electrical efficiency. A CHP or CCHP energy technology has two efficiencies as they produce both electric and thermal energy. Thus, in such cases the total fuel to total output efficiency is the sum of effective electrical output and effective thermal output efficiencies [117]. Grid electricity efficiency is the product of the local utility power plant efficiency and transmission and distribution efficiency (~0.94). Storage device efficiency is the product of grid electricity and storage technology efficiency. The advantage of a storage technology is that its reliability is comparatively higher than the grid electricity alone. We collect efficiencies data for energy technologies and end-uses from multiple sources [3] [116] [117] [118] [119] [120].

Energy Technology Efficiencies			
Energy Technology	Fuel to Total Output	Effective Electrical Output	Effective Thermal Output
Grid electricity	0.30	0.30	-
Grid electricity with battery storage	0.24	0.24	-
Grid electricity with pumped water storage	0.23	0.23	-
Grid electricity with compressed air storage	0.20	0.20	-
Grid electricity with hydrogen storage	0.11	0.11	-
Diesel engine electricity	0.42	0.42	-
Diesel engine CHP	0.77	0.42	0.35
Diesel engine CCHP	0.77	0.42	0.35
Biodiesel engine electricity	0.39	0.39	-
Biodiesel engine CHP	0.69	0.39	0.30
Biodiesel engine CCHP	0.69	0.39	0.30
Gas engine electricity	0.39	0.39	-
Gas engine CHP	0.74	0.39	0.35
Gas engine CCHP	0.74	0.39	0.35
Gas turbine electricity	0.37	0.37	-
Gas turbine CHP	0.72	0.37	0.35
Gas turbine CCHP	0.72	0.37	0.35
Gas microturbine electricity	0.27	0.27	-
Gas microturbine CHP	0.68	0.27	0.41
Gas microturbine CCHP	0.68	0.27	0.41
Biomass-direct electricity	0.35	0.35	-
Biomass-direct CHP	0.70	0.35	0.35
Biomass-direct CCHP	0.70	0.35	0.35
Polymer electrolyte membrane fuel cells elect	0.35	0.35	-
Polymer electrolyte membrane fuel cells CHP	0.72	0.35	0.37
Phosphoric acid fuel cells electricity	0.42	0.42	-
Phosphoric acid fuel cells CHP	0.81	0.33	0.48
Molten carbonated fuel cells electricity	0.55	0.55	-
Molten carbonated fuel cells CHP	0.62	0.43	0.19
Solid oxide fuel cells electricity	0.60	0.60	-
Solid oxide fuel cells CHP	0.77	0.43	0.34
Wind turbine- onshore electricity	0.48	0.48	-
Solar photovoltaic-thin film electricity	0.15	0.15	-
Solar photovoltaic- crystalline electricity	0.18	0.18	-
Parabolic trough solar thermal electricity	0.18	0.18	-
Central receiver solar thermal electricity	0.28	0.28	-
Solar thermal collector water heater	0.69	-	0.69
Solar thermal collector furnace	0.61	-	0.61
Solar thermal collector with adsorption chiller	0.61	-	0.61
Fuel oil water heater	0.80	-	0.80
Gas water heater	0.90	-	0.90
Oil-fired furnace / boiler	0.78	-	0.78
Gas-fired furnace / boiler	0.81	-	0.81
Biomass fired boiler	0.75	-	0.75
Geothermal pump	0.86	-	0.86
Geothermal pump with desuperheater	0.86	-	0.86

Table 1. Energy Technology Efficiencies

End-Use	Efficiency	Notes
Water Pumping	0.61	Motor and pump efficiency, frictional and line loses are neglected as they vary by buildings
Water Heating	1.00	Electric heating element has efficiency of 1
Water Heating by CHP/CCHP	0.98	Hot water is the transfer medium for heating and has a typical 2% insulation loss
Space Heating	1.00	Electric heating element has efficiency of 1
Space Heating by CHP/CCHP	0.95	Hot water is the transfer medium and has a typical 5% convection and radiation losses
Ventilation	0.90	Electric motor and duct blower efficiency
Space Cooling	0.61	Central air conditioning compressor efficiency
Space Cooling by CCHP	0.95	Adsorption chiller efficiency, chiiled water is the transfer medium for cooling
Refrigeration	0.41	Reciprocating compressor mechanical efficiency
Lighting	0.22	Fluorescent lamps efficiency
Electrical and Electronic Equipment	0.72	Average and appoximate efficiency of common appliances /equipment

Table 2. End-Use Efficiencies

System efficiency implies efficiency of energy (kWh) conversion from the fuel to the end-use [121]. For example, the fuel to electric energy output efficiency of a diesel reciprocating engine is about 0.42 and the end-use device efficiency of an electric motor pump which is used for water pumping is 0.61. The net system efficiency of every kWh of energy of diesel electricity used for water pumping is 0.42*0.61 = 0.26. In case of CHP and CCHP systems, the system efficiency is the product of the respective effective electric output efficiency (for electric energy end-uses) or effective thermal output efficiency (for thermal energy end-uses) and the end-use efficiency. For energy technologies with thermal output only, the system efficiency equals the energy technology alone. Table 3 shows the estimated system efficiencies for all the energy technology and end-use combinations. A dash implies that the respective combination is not feasible. High system efficiency leads to a lesser waste of energy and thus, a relatively lesser operating cost and environmental impact [122] [123]. Fuel to output efficiency data is used to proportionate the costs. The system efficiency data is used to calculate the emissions released by each technology and end-use combination.

	u	1	2	3	4	5	6	7	8
t		Water pumping	Water heating	Space heating	Ventilation	Space cooling	Refrigeration	Lighting	Electricals and Electronics
1	Grid electricity	0.18	0.30	0.30	0.27	0.18	0.27	0.07	0.22
2	Grid electricity with battery storage	0.15	0.24	0.24	0.22	0.15	0.22	0.05	0.17
3	Grid electricity with pumped water storage	0.14	0.23	0.23	0.20	0.14	0.20	0.05	0.16
4	Grid electricity with compressed air storage	0.12	0.20	0.20	0.18	0.12	0.18	0.04	0.14
5	Grid electricity with hydrogen storage	0.06	0.11	0.11	0.09	0.06	0.09	0.02	0.08
6	Diesel engine electricity	0.26	0.42	0.42	0.38	0.26	0.38	0.09	0.30
7	Diesel engine CHP	0.26	0.34	0.33	0.38	0.21	0.38	0.09	0.30
8	Diesel engine CCHP	0.26	0.34	0.33	0.38	0.33	0.38	0.09	0.30
9	Biodiesel engine electricity	0.24	0.39	0.39	0.35	0.24	0.35	0.09	0.28
10	Biodiesel engine CHP	0.24	0.30	0.29	0.35	0.18	0.35	0.09	0.28
11	Biodiesel engine CCHP	0.24	0.30	0.29	0.35	0.29	0.35	0.09	0.28
12	Gas engine electricity	0.24	0.39	0.39	0.35	0.24	0.35	0.09	0.28
13	Gas engine CHP	0.24	0.34	0.33	0.35	0.21	0.35	0.09	0.28
14	Gas engine CCHP	0.24	0.34	0.33	0.35	0.33	0.35	0.09	0.28
15	Gas turbine electricity	0.23	0.37	0.37	0.33	0.23	0.33	0.08	0.27
16	Gas turbine CHP	0.23	0.34	0.33	0.33	0.21	0.33	0.08	0.27
17	Gas turbine CCHP	0.23	0.34	0.33	0.33	0.33	0.33	0.08	0.27
18	Gas microturbine electricity	0.16	0.27	0.27	0.24	0.16	0.24	0.06	0.19
19	Gas microturbine CHP	0.16	0.40	0.39	0.24	0.25	0.24	0.06	0.19
20	Gas microturbine CCHP	0.16	0.40	0.39	0.24	0.39	0.24	0.06	0.19
21	Biomass-direct electricity	0.21	0.35	0.35	0.32	0.21	0.32	0.08	0.25
22	Biomass-direct CHP	0.21	0.34	0.33	0.32	0.21	0.32	0.08	0.25
23	Biomass-direct CCHP	0.21	0.34	0.33	0.32	0.33	0.32	0.08	0.25
24	Polymer electrolyte membrane fuel cells electricity	0.21	0.35	0.35	0.32	0.21	0.32	0.08	0.25
25	Polymer electrolyte membrane fuel cells CHP	0.21	0.36	0.35	0.32	0.23	0.32	0.08	0.25
26	Phosphoric acid fuel cells electricity	0.26	0.42	0.42	0.38	0.26	0.38	0.09	0.30
27	Phosphoric acid fuel cells CHP	0.20	0.47	0.46	0.30	0.29	0.30	0.07	0.24
28	Molten carbonated fuel cells electricity	0.34	0.55	0.55	0.50	0.34	0.50	0.12	0.40
29	Molten carbonated fuel cells CHP	0.26	0.19	0.18	0.39	0.12	0.39	0.09	0.31
30	Solid oxide fuel cells electricity	0.37	0.60	0.60	0.54	0.37	0.54	0.13	0.43
31	Solid oxide fuel cells CHP	0.26	0.33	0.32	0.39	0.21	0.39	0.09	0.31
32	Wind turbine- onshore electricity	0.29	0.48	0.48	0.43	0.29	0.43	0.11	0.35
33	Solar photovoltaic-thin film electricity	0.09	0.15	0.15	0.14	0.09	0.14	0.03	0.11
34	Solar photovoltaic- crystalline electricity	0.11	0.18	0.18	0.16	0.11	0.16	0.04	0.13
35	Parabolic trough solar thermal electricity	0.11	0.18	0.18	0.16	0.11	0.16	0.04	0.13
36	Central receiver solar thermal electricity	0.17	0.28	0.28	0.25	0.17	0.25	0.06	0.20
37	Solar thermal collector water heater	-	0.69	-	-	-	-	-	-
38	Solar thermal collector furnace	-	-	0.61	-	-	-	-	-
39	Solar thermal collector with adsorption chiller	-	-	0.61	-	0.58	-	-	-
40	Fuel oil water heater	-	0.80	-	-	-	-	-	-
41	Gas water heater	-	0.90	-	-	-	-	-	-
42	Oil-fired furnace / boiler	-	-	0.78	-	-	-	-	-
43	Gas-fired furnace / boiler	-	-	0.81	-	-	-	-	-
44	Biomass fired boiler	-	0.75	0.75	-	-	-	-	-
45	Geothermal pump	-	-	0.86	-	0.86	-	-	-
46	Geothermal pump with desuperheater	-	0.86	-	-	-	-	-	-

Table 3. System Efficiencies

3.2. Metrics

The DER technologies must be compared and evaluated relative to each other to select the optimal technology for specific energy uses [122] [9] [113]. Thus, we evaluate the performance of each DER technology relative to an empirical production possibility frontier determined by all the DER technologies for a particular end-use under appropriate assumptions. We evaluate each energy technology and end-use combination using three objectives simultaneously – economic, technical, and environmental.

For the economic objective, we consider levelized cost (LC). LC (cents per kWh) is the constant unit cost per every kWh of energy that is supplied. LC summarizes the overall cost of the energy technology throughout its life [24]. LC accounts for turnkey, operating and maintenance (O&M), fuel, and financial costs throughout the life of the equipment. We consider LC in 2013 dollars with a 20 year economic life/duty cycle of a consistent 500kW power capacity for all technologies (except grid electricity), with a 40% tax rate, 30% debt, 1% degradation, 25% fuel escalation, and 8% interest rate. We obtain other necessary LC components such as turnkey costs, O&M costs, and capacity factors from Borbely and Kreider [3]. We assume a diesel price of $3.75 per gallon and a natural gas price of $8.00 per MMBtu (1 MMBtu = 293.3 kWh). We do not include government incentives or credits and operator profits. We adjust the LC for CHP and CCHP technologies proportional to the total electric and thermal energy that is output by the technology [124] [117]. The LC data is available through several sources such as [69], [125], [24], and [126].

For the technical objective, we consider the reliability factor (RF). RF (ratio) is a combined measure of the availability of a fuel source and the technical or mechanical reliability of the technology to supply every kWh of energy for an end-use. Power reliability problems range from the occasional voltage variations (brown-out) to complete power loss (black-out) due to overload or external disturbances to the power system. RF for renewable technologies depends on the season and climate conditions [127]. For example, the RF of solar energy technology used for space heating (which usually has demand in cold weather) is higher than the RF of solar energy technology used for space cooling (which usually has demand in warm weather**).** We estimate the RF of different energy resources by compiling the performance and reliability data such as fuel sources availability (for solar, wind, biomass, etc.) from 2012 Renewable Energy Data Book [127], and typical technical failures for technologies (for grid, gas turbines, etc.) from multiple sources [119] [128]. The RF data varies by region due to local utility grid and weather conditions. The National Renewable Energy Laboratory (NREL) [127] and the National Energy Technologies Laboratory (NETL) [129] furnish data on the reliability of energy output by renewable energy technologies for different regions across the US.

For the environmental objective, we consider three emissions (EM) – Carbon, Nitrogen, and Sulfur. Carbon (C) emission is a major greenhouse gas (GHG) [130]. The U.S. Environment and Protection Agency (EPA) emphasizes policies to reduce the carbon footprint from energy generation as it is more accessible to monitor and control from power generating stations than from millions of vehicles [131]. Nitrogen (N) and Sulfur (S) emissions contribute to rainfall acidity [132]. The Clean Air Act requires the EPA to set national air quality standards for six pollutants – carbon, nitrogen, sulfur, particulate matter, ozone, and lead [133]. This study does not include coal and oil power generating plants as they are not feasible for distributed energy generation [9]. Thus, we do not consider particulate matter, lead, and ozone pollutants as they are of significant concern only for large scale coal and oil power plants [28]. We do not consider indirect emissions that are released during the design, manufacturing, or construction stages.

We obtain the composition and enthalpy values (higher heating value) of the fuels from an engineering handbook and compute EM (grams per kWh) using stoichiometry equations, relevant system efficiencies, and other principles of combustion such as exergy [134] [135] [130] [119]. For example, Diesel fuel has 87% Carbon (C) content and the calorific value (higher heating value) is 43,820 kJ/kg (or 12.17 kWh/kg) [134]. The C emission for every kWh produced during the combustion process is 71.48g of C/kWh. To find the net C emission at the end-use, the calculated C emission is divided by the system efficiency of each combination. For example, the quantity of C emitted for water pumping using diesel electricity is (71.48 g of C/kWh)/ 0.26 = 274.95 g of C/kWh. In the same fashion, we calculate the N and S emissions. Antipova et al. [136] propose to optimize the energy system with a reduced number of environmental objectives that fully describe the system's performance but eliminate redundant criteria from the analysis. Thus, in order to remove the redundancy of objectives, we aggregate the three pollutants into one quantity (EM). We compute the EM for CHP and CCHP technologies proportional to the useful electric and thermal energy that is output by the technology using the effective system efficiencies data [76] [117]. EM data for the grid electricity is obtained from the local utility reports and varies by the region or the locality.

The LC, RF, and EM data for all the energy technology and end-use combinations is shown in chapter 5 (actual values in tables 5a, 5b, 5c, 5d, 5e, 5f, 5g, and 5h) for a particular scenario. Note that the emphasis of this dissertation lies in presenting and demonstrating the novel DER framework. Energy decision makers seek solutions that satisfy multiple objectives that are often conflicting [137]. Particularly balancing energy costs and environmental attributes pose a major dilemma in energy decision analysis [138] . In order to achieve the desired levels of these objectives, it is often important to allocate the energy resources efficiently [139]. This is the fundamental idea behind incorporating the three objectives discussed previously into a non-parametric production frontier methodology. We obtain the three factor efficiency scores for each energy technology and end-use combination from this process. This constitutes the first stage of the framework. Figure 2 summarizes the description of the three objectives.

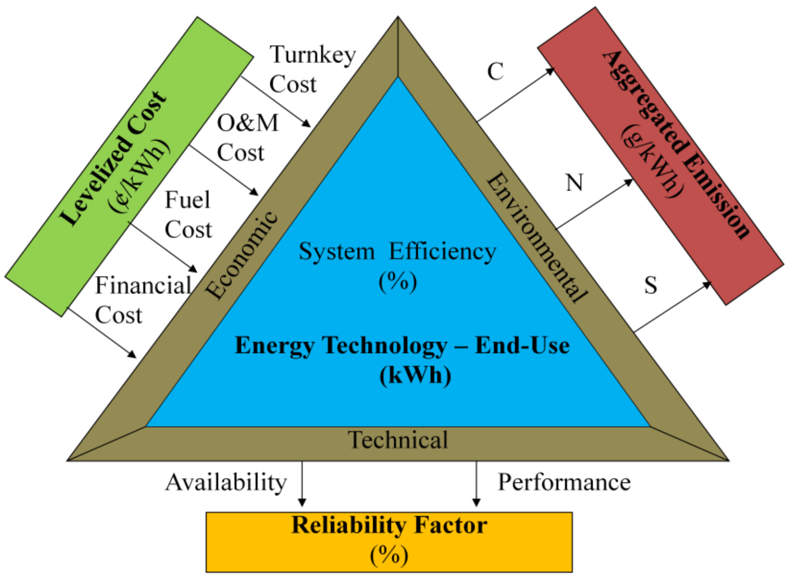


Figure 2. The Three Objectives

We incorporate the factor efficiency scores obtained from the first stage into a multi-criteria methodology. In particular, the factor efficiency scores appear as coefficients of the decision variables in a set of constraints designed to produce solutions that simultaneously consider the objectives in a balanced fashion by eliminating the subjectivity of weights [140]. In addition, supplementary operational criteria and constraints are incorporated in the multi-criteria methodology to obtain the optimal energy resource to end-use allocation. This constitutes the second stage of the framework.

Chapter 4

Methodology

In an energy planning models review paper, Loken [35] justifies that researchers should use more than one methodology, either in combination to make use of the strengths of both methodologies, or in parallel to attain a perceptible decision basis for an energy decision maker. Thus, we develop a hybrid two-method two-stage framework to study DER technology competitiveness and allocation while accounting for the three objectives simultaneously. This chapter describes the methodology of the framework comprehensively.

4.1. Energy Technologies and End-Uses

Table 4 shows the energy technology (t) and end-use (u) matrix. There are 46 (T) technologies and 8 (U) end-uses. The cells represent allowable energy capacities in kWh (C_{tu}) for the particular energy technology (t) and end-use (u) combination. The "M" signifies a big M value, meaning that there is a high capacity limit for the corresponding combination. The big M can be substituted with a limit value (kWh) in case there is an actual capacity restriction, such as land available for wind or solar technologies, fuel supply limitations, or biomass availability, etc. Zero implies that the respective energy technology (*t*) cannot be used for the corresponding end-use (*u*). For example, geothermal pump technology cannot be used for water pumping, and the solar thermal collector resource captures thermal energy from the sun rays that can be used for space heating and water heating only. We consider the energy technologies that are commercially available and are not in the development or the demonstration phase [3]. We consider the energy end-uses that are most common for a typical commercial user [141]. Energy technologies and end-uses can be added or removed according to the user, resource availability, etc. This makes the framework adaptable to any DER situation.

t	u	1	2	3	4	5	6	7	8
t	C_{tu}	Water pumping	Water heating	Space heating	Ventilation	Space cooling	Refrigeration	Lighting	Electricals and Electronics
1	Grid electricity	M	M	M	M	M	M	M	M
2	Grid electricity with battery storage	M	M	M	M	M	M	M	M
3	Grid electricity with pumped water storage	M	M	M	M	M	M	M	M
4	Grid electricity with compressed air storage	M	M	M	M	M	M	M	M
5	Grid electricity with hydrogen storage	M	M	M	M	M	M	M	M
6	Diesel engine electricity	M	M	M	M	M	M	M	M
7	Diesel engine CHP	M	M	M	M	M	M	M	M
8	Diesel engine CCHP	M	M	M	M	M	M	M	M
9	Biodiesel engine electricity	M	M	M	M	M	M	M	M
10	Biodiesel engine CHP	M	M	M	M	M	M	M	M
11	Biodiesel engine CCHP	M	M	M	M	M	M	M	M
12	Gas engine electricity	M	M	M	M	M	M	M	M
13	Gas engine CHP	M	M	M	M	M	M	M	M
14	Gas engine CCHP	M	M	M	M	M	M	M	M
15	Gas turbine electricity	M	M	M	M	M	M	M	M
16	Gas turbine CHP	M	M	M	M	M	M	M	M
17	Gas turbine CCHP	M	M	M	M	M	M	M	M
18	Gas microturbine electricity	M	M	M	M	M	M	M	M
19	Gas microturbine CHP	M	M	M	M	M	M	M	M
20	Gas microturbine CCHP	M	M	M	M	M	M	M	M
21	Biomass-direct electricity	M	M	M	M	M	M	M	M
22	Biomass-direct CHP	M	M	M	M	M	M	M	M
23	Biomass-direct CCHP	M	M	M	M	M	M	M	M
24	Polymer electrolyte membrane fuel cells electricity	M	M	M	M	M	M	M	M
25	Polymer electrolyte membrane fuel cells CHP	M	M	M	M	M	M	M	M
26	Phosphoric acid fuel cells electricity	M	M	M	M	M	M	M	M
27	Phosphoric acid fuel cells CHP	M	M	M	M	M	M	M	M
28	Molten carbonated fuel cells electricity	M	M	M	M	M	M	M	M
29	Molten carbonated fuel cells CHP	M	M	M	M	M	M	M	M
30	Solid oxide fuel cells electricity	M	M	M	M	M	M	M	M
31	Solid oxide fuel cells CHP	M	M	M	M	M	M	M	M
32	Wind turbine- onshore electricity	M	M	M	M	M	M	M	M
33	Solar photovoltaic-thin film electricity	M	M	M	M	M	M	M	M
34	Solar photovoltaic- crystalline electricity	M	M	M	M	M	M	M	M
35	Parabolic trough solar thermal electricity	M	M	M	M	M	M	M	M
36	Central receiver solar thermal electricity	M	M	M	M	M	M	M	M
37	Solar thermal collector water heater	0	M	0	0	0	0	0	0
38	Solar thermal collector furnace	0	0	M	0	0	0	0	0
39	Solar thermal collector with adsorption chiller	0	0	0	0	M	0	0	0
40	Fuel oil water heater	0	M	0	0	0	0	0	0
41	Gas water heater	0	M	0	0	0	0	0	0
42	Oil-fired furnace / boiler	0	0	M	0	0	0	0	0
43	Gas-fired furnace / boiler	0	0	M	0	0	0	0	0
44	Biomass fired boiler	0	M	M	0	0	0	0	0
45	Geothermal pump	0	0	M	0	M	0	0	0
46	Geothermal pump with desuperheater	0	M	0	0	0	0	0	0

Table 4. Energy Technologies and End-Uses

Grid electricity (*t*=1) is the energy available from the local utility grid. There are four storage technologies (*t*=2,3,4,5) that can be used in conjunction with grid supply in order to increase reliability and/or to store energy during the off-peak hours to lower energy consumption costs [126]. These together will allow a DER system to be grid-integrated.

There are ten Combined Heat and Power (CHP) technologies (*t*=7,10,12,16,19,22,25,27,29,31) and six Combined Cooling, Heating and Power (CCHP) technologies (*t*=8,11,14,17,20,23). CHP or CCHP are not specific energy technologies but are applications to energy technologies that increase the useful energy output and improve efficiency. In a CHP technology, when electric energy is generated, thermal energy (or heat) produced during the generation process is captured and used for space heating and water heating (*u*=2, 3). In CCHP, the heat captured is used for either space heating (on cold days) or for space cooling (on warm days) while being used constantly for water heating [142] [143]. Thus, CHP and CCHP technologies provide thermal energy (versus electric energy) for heating and cooling (*u*=2, 3, 5) [144]. In most cases, CCHP is not suitable for commercial refrigeration (*u*=6) as it requires heavy cooling loads which cannot be fulfilled with CCHP [145]. CCHP uses an adsorption chiller that utilizes thermal energy to cool the water [146]. Chilled water acts as a transfer medium for space cooling, whereas commercial refrigeration typically requires compressors with ammonia or Freon refrigerants to achieve high cooling power [147].

Energy technologies (*t*=37 to 46) such as heaters, furnaces, thermal collectors, and heat pumps provide only thermal energy for heating and cooling end-uses (*u*=2, 3, 5). Thus, they tend to have the lowest costs among all the technologies.

4.2. First Stage of the Framework

In the first stage of the framework, we use unoriented Data Envelopment Analysis (DEA) to compute factor efficiencies of each energy technology ($t = 1,\ldots, T$) for each end-use ($u = 1,\ldots, U$). DEA is a linear programming based non-parametric methodology that measures the efficiency of each technology relative to an empirical production possibility frontier determined by all technologies under appropriate assumptions regarding model orientation and returns to scale. [148].

Typically, DEA models are either input oriented or output oriented [149]. An input oriented model reduces inputs as much as possible while maintaining output levels. An output oriented model increases outputs as much as possible while maintaining input levels. In addition, DEA models can be unoriented [150]. An unoriented DEA model can be used to measure efficiency in situations in which analysts seek to simultaneously reduce input quantities and increase output quantities.

The production possibility frontier's function depends on the type of returns to scale assumption the DEA model follows. See figure 3 for a simple one-input, one-output depiction. DEA models can be constant return to scale (CRS), non-decreasing returns to scale, non-increasing returns to scale, or variable returns to scale (VRS). In CRS models, technologies are able to linearly scale inputs and outputs without decreasing or increasing the technology's efficiency. In non-decreasing returns to scale models, proportionate increases in all of the inputs result in more than proportionate increases in its outputs, while in non-increasing returns to scale models, proportionate increases in inputs result in less than proportionate increases in outputs [151]. VRS models are a combination of both non-decreasing and non-increasing returns to scale models. For thorough review of DEA, the reader can refer to Sexton [152] and Sexton and Silkman [153].

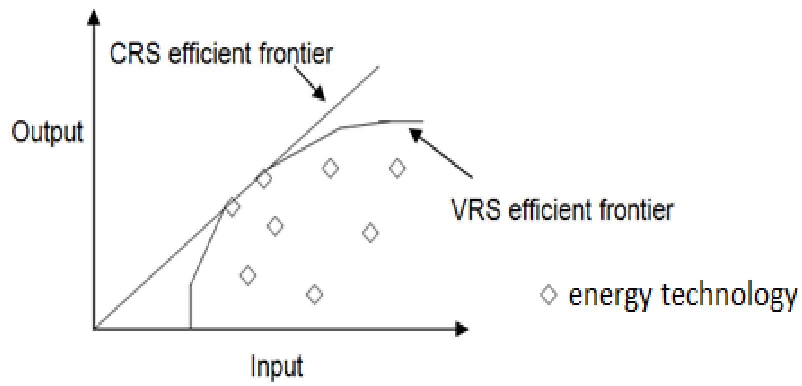


Figure 3. DEA CRS and VRS Frontiers

DEA converts a specific level of each input into a specific level of each output. DEA is applicable in situations where the inputs and outputs are in different units and cannot be precisely converted to a common scale, as is the case here. LC (cents/kWh) is the input and RF (ratio) and EM (grams/kWh) are the outputs for the technologies. We use the unoriented DEA model as DER decision makers seek to decrease the input and increase the outputs concurrently [99]. EM is a reverse quantity output [154] i.e., though it is an output, less quantity is desired. To achieve meaningful results, the proposed DEA model follows the constant returns to scale (CRS) assumption. This assumption is justified as the inputs and outputs are constant values expressed per kWh of energy production.

We perform the DEA model for each end-use separately. The DEA model for an energy technology *k* in an end-use *u* is formulated as follows:

$$\text{Min}\,\varepsilon_{ku}\,\text{or Max}\,\theta_{ku} \qquad \text{Eq. 1}$$

subject to

$$\sum_{t=1}^{T} \lambda_{ktu}(\text{LC})_{tu} \le \varepsilon_{ku}(\text{LC})_{ku} \qquad \text{Eq. 2}$$

$$\sum_{t=1}^{T} \lambda_{ktu}(\text{RF})_{tu} \ge \theta_{ku}(\text{RF})_{ku} \qquad \text{Eq. 3}$$

$$\sum_{t=1}^{T} \lambda_{ktu}(\text{EM})_{tu} \le \varepsilon_{ku}(\text{EM})_{ku} \qquad \text{Eq. 4}$$

$$\varepsilon_{ku} + \theta_{ku} = 2 \qquad \text{Eq. 5}$$

$$\lambda_{ktu} \ge 0 \;\; \text{for}\; t = 1,\ldots,T \qquad \text{Eq. 6}$$

$$\varepsilon_{ku}, \theta_{ku} \ge 0 \qquad \text{Eq. 7}$$

Where,

- λ_{ktu} is the weight placed on the energy technology *t* for an end-use *u* by the energy technology *k*.
- ε_{ku} is the relative efficiency of the energy technology *k* for end-use *u*.
- θ_{ku} is the approximate inverse efficiency of the energy technology *k* for end-use *u*.

Equation 1 minimizes the relative efficiency of the energy technology *k* or equivalently maximizes its approximate inverse efficiency. Equation 2 ensures the hypothetical target energy technology consumes no more of the input (LC) than the energy technology *k*. Equation 3 ensures the hypothetical target energy technology produces at least as much of the output (RF) as does the energy technology *k*. Equation 4 ensures the hypothetical target energy technology produces no more of the reverse quantity output (EM) than the energy technology *k*. Equation 5 is a first-order linear approximation of $\varepsilon_{ku}{*}\ \theta_{ku}$ =1 [155]. Equations 6 and 7 ensure that the decision variables are non-negative.

The three factor efficiencies for energy technology k for end-use u are given by:

$$F_{1ku} = \frac{\sum_{t=1}^{T} \lambda_{ktu} (\text{LC})_{tu}}{(\text{LC})_{ku}} \qquad \text{Eq. 8}$$

$$F_{2ku} = \frac{(\text{RF})_{ku}}{\sum_{t=1}^{T} \lambda_{ktu} (\text{RF})_{ku}} \qquad \text{Eq. 9}$$

$$F_{3ku} = \frac{\sum_{t=1}^{T} \lambda_{ktu} (\text{EM})_{tu}}{(\text{EM})_{ku}} \qquad \text{Eq. 10}$$

Equations 8, 9, and 10 estimate the factor efficiency scores for the three objectives LC, RF, and EM, respectively. At optimality: $F_{1ku} \leq \varepsilon_{ku}$, $F_{2ku} \leq 1/\Theta_{ku}$, and $F_{3ku} \leq \varepsilon_{ku}$. As shown in equation 8, the factor efficiency score for LC (for energy technology k and end-use u) is the ratio of its efficient target value to its actual value. As shown in equation 9, the factor efficiency score for RF (for energy technology k and end-use u) is the ratio of its actual value to its efficient target value. As shown in equation 10, the factor efficiency score for EM (for energy technology k and end-use u) is the ratio of its efficient target value to its actual value. The key idea in this stage is that the DER decision maker desires to choose energy technology k if it scores high factor efficiencies, and reject if it scores low factor efficiencies. We embody this concept in the second stage of the framework by incorporating the factor efficiencies scores into a multi-criteria decision methodology.

4.3. Second Stage of the Framework

In the second stage, we use Goal Programming (GP) to obtain the optimal energy resource and end-use allocation while accounting for additional constraints. GP is a commonly used multi-criteria decision methodology that is capable of handling multiple objectives (goals) within the general framework of linear programming [156] [157]. However, GP requires target values and unit penalty weights associated with each goal. It is difficult to specify these values consistently as the objectives are contradictory and thus pose a problem of subjectivity [158] [159] [140].

We mitigate this issue in the proposed framework by incorporating the factor efficiencies scores estimated by the DEA models into the GP-bottleneck model. We employ the GP-bottleneck model proposed by Lewis [140]. The GP-bottleneck model includes constraints on the energy resources capacity restraints (C_{tu}) and constraints that ensure that the optimal energy technology to end-use allocation (Q_{tu}) will not be less than the given end-use demands (D_u) in a DER system.

We apply the GP-bottleneck methodology for all energy technologies ($t = 1,\dots, T$) and end-uses ($u = 1,\dots, U$). The GP-bottleneck model is formulated as follows:

$$\text{Min}\, B \qquad \text{Eq. 11}$$

subject to

$$\sum_{t=1}^{T}\sum_{u=1}^{U}\left(\frac{1}{F_{1tu}}\right)Q_{tu} \le B \qquad \text{Eq. 12}$$

$$\sum_{t=1}^{T}\sum_{u=1}^{U}\left(\frac{1}{F_{2tu}}\right)Q_{tu} \le B \qquad \text{Eq. 13}$$

$$\sum_{t=1}^{T}\sum_{u=1}^{U}\left(\frac{1}{F_{3tu}}\right)Q_{tu} \le B \qquad \text{Eq. 14}$$

$$Q_{tu} \le C_{tu} \quad \text{for } t = 1,\ldots,T \text{ and } u = 1,\ldots,U \qquad \text{Eq. 15}$$

$$\sum_{t=1}^{T} Q_{tu} \ge D_u \quad \text{for } u = 1,\ldots,U \qquad \text{Eq. 16}$$

$$Q_{tu} \ge 0 \quad \text{for } t = 1,\ldots,T \text{ and } u = 1,\ldots,U \qquad \text{Eq. 17}$$

$$B \ge 0 \qquad \text{Eq. 18}$$

Where,

- B is the bottleneck variable
- Q_{tu} is the energy allocation in kWh for energy technology t and end-use u.
- C_{tu} is the allowable energy capacity in kWh for energy technology t and end-use u.
- D_u is the energy demand in kWh for end-use u.

Equation 11 is the objective function that minimizes the bottleneck variable (B). Equations 12, 13, and 14 ensure that all three objectives are considered simultaneously when selecting the energy technology allocation. This ensures that no one objective dominates the others. Equation 15 ensures that the allocated energy capacity (Q_{tu}) is no more than the allowable energy capacity (C_{tu}) for respective energy technology (t) and end-use (u). Equation 16 guarantees that the allocated energy capacity (Q_{tu}) for an end-use is at least as much as the energy demand (D_u) for that end-use. Equations 17 and 18 ensure that the decision variables are non-negative.

CHP technologies produce two forms of energy. Electric energy is used for end-uses (*u*=1, 4, 5, 6, 7, 8) and thermal energy is used for end-uses (*u*=2,3). Thus, we embody this principle by integrating additional constraints for CHP technologies *t* =7, 10, 13, 16, 19, 22, 25, 27, 29, 31.

$$Q_{t3} = h_t(Q_{t1} + Q_{t4} + Q_{t5} + Q_{t6} + Q_{t7} + Q_{t8}) \quad \text{Eq. 19}$$
$$Q_{t2} = w_t Q_{t3} \quad \text{Eq. 20}$$

h_t is the heat to power ratio for the CHP or CCHP energy technology *t* [117]. For illustration, say a CHP energy technology produces 30 units (kWh_e) of electricity, and as a result 45 units (kWh_t) of thermal energy is captured and supplied. Thus the heat to power ratio (h_t) of this CHP technology is computed as 45/30=1.5 (unitless) [117]. w_t is the residual heat ratio that is available for water heating (*u*=2) through the CHP energy technology *t* [117]. The values of h_t and w_t vary for different CHP technologies. The data for h_t and w_t is provided in the catalog of CHP technologies document prepared by the EPA [117].

Equation 19 ensures that the thermal energy available for space heating (*u*=3) through the CHP energy technology *t* is equal to h_t times the cumulative electric energy produced for other end-uses (*u*=1, 4, 5, 6, 7, 8). After the captured heat passes through a heat exchanger for space heating (*u*=3), the residual heat that exits the heat exchanger is used for water heating (*u*=2). Thus, equation 20 ensures that the thermal energy available for water heating (*u*=2) through a CHP technology *t* is equal to w_t times the thermal energy available for space heating end-use (*u*=3). In case of CHP technologies, space cooling end-use (*u*=5) is satisfied with electric energy.

Similarly, CCHP technologies produce two forms of energy. Electric energy is used for end-uses (*u*=1,4,6,7,8) and thermal energy is used for end-uses (*u*=2,3,5). In the case of CCHP technologies, space cooling (u=5) is satisfied with thermal energy. Thus, we embody this principle by integrating additional constraints for CCHP technologies t =8, 11, 14, 17, 20, 23.

$$Q_{t3} = Q_{t5} = h_t (Q_{t1} + Q_{t4} + Q_{t6} + Q_{t7} + Q_{t8}) \quad \text{Eq. 21}$$
$$Q_{t2} = w_t Q_{t3} = w_t Q_{t5} \quad \text{Eq. 22}$$

In CCHP technologies, the heat captured h_t is used for either space heating during cold days or for space cooling during warm days (u=3, 5). Space heating and space cooling end-uses are mutually exclusive (HVAC systems). Thus, equation 21 ensures that the thermal energy available for either space heating or space cooling (u=3, 5) through the CCHP energy technology t is equal to h_t times the cumulative electric energy produced for other end-uses (u=1, 4, 6, 7, 8). The residual heat w_t that exits either from the heat exchanger (in case of space heating) or adsorption chiller (in case of space cooling) is used for water heating (u=2). Hence, equation 22 ensures that the thermal energy available for water heating (u=2) through a CCHP technology t is equal to w_t times the thermal energy available for space heating or space cooling (u=3, 5).

Finally, the constraints for geothermal pump technology are:

$$Q_{45,3} = \alpha Q_{45,5} \quad \text{Eq. 23}$$
$$Q_{46,2} = w Q_{45,3} \quad \text{Eq. 24}$$

Geothermal pump technology (t=45) is used for space heating during winter and space cooling during summer. α is the heating (at 32°F) to cooling (at 77°F) ratio for geothermal pump technology [160]. A ground loop geothermal heat pump with an approximate cooling capacity of 100 units will result in an approximate 74 units of heating capacity, thus α is = 0.74 (unitless)

[161]. w is the percent of thermal energy available for water heating (u=2) through geothermal pump technology in conjunction with the desuperheater technology (t=46) [162].

Thus, equation 23 ensures that the energy available for space heating (u=3) through the geothermal energy technology (t=45) is equal to α times the energy available for space cooling (u=5). Equation 24 ensures that the thermal energy available for water heating (u=2) through the geothermal energy technology (t=46) is equal to w times the thermal energy available for space heating (u=3).

Various end-uses have different levels of significance and requirements [163]. Thus, end-uses have various minimum energy requirements or dispatchability [164]. Dispatchability is a minimum end-use energy demand that should be available all the time. The minimum dispatchability differs for various end-uses [165]. An end-use u with a low minimum dispatchability reflects that there is a high portion of the energy demand of end-use u that can be rescheduled by load shedding or load controlling [166] [1]. End-uses such as water pumping and water heating tend to have low minimum dispatchability and critical end-uses such as space heating and refrigeration tend to have high minimum dispatchability [1]. The inclusion of dispatchability enhances the optimal allocation framework by interacting the dispatchability of various end-uses' energy demands with the dispatchability of energy technologies [167].

Minimum dispatchability (d_u) for an end use u is the percent of total energy demand D_u for end-use u, thus $0 \le d_u \le 1$. The following constraint accounts for minimum dispatchability (d_u) for each end-use.

$$\sum_{t=1}^{T} P_t Q_{tu} \geq d_u D_u \quad \text{for } u = 1,\dots,U \qquad \text{Eq. 25}$$

P_t signifies whether the energy technology t is dispatchable (P_t =1) or not dispatchable (P_t =0). Equation 25 ensures that the target allocated dispatchable energy capacity for each end-use u is at least as much as the minimum dispatchable demand for respective end-use u.

U.S. energy policy promotes renewable energy generation and targets that the renewable energy penetration should be about 29% in New York by 2015 and 33% in California by 2020 [24]. DER systems are one of the potential ways to increase renewable energy penetration swiftly [111] [9] [7]. Thus, we embody a “minimum renewable energy penetration” policy variable into the framework. The policy variable enables decision makers to examine the alteration of energy technology selection, optimal energy allocation, costs, and emissions by changing its value. This allows the regulatory bodies to determine policies that can encourage (or restrict) the DER developers, users, and operators to consider certain renewable energy technologies depending on the end-uses, related energy demands, and dispatchability.

Minimum renewable penetration (r) is the percent of total energy demand D_u for all end-uses u=1,…,U, thus $0 \leq r \leq 1$. The following constraint accounts for cumulative minimum renewable penetration (r) for total energy demand by all end-uses.

$$\sum_{t=1}^{T}\sum_{u=1}^{U} R_t Q_{tu} \geq r \sum_{u=1}^{U} D_u \qquad \text{Eq. 26}$$

R_t signifies whether the energy technology t is a renewable source (R_t =1) or non-renewable source (R_t =0). Equation 26 ensures that the target allocated renewable energy capacity for all the end-uses u is at least as much as the cumulative minimum renewable energy demand for all end-uses.

Dispatchability and renewable energy penetration constraints accommodate DER end-use demand requirements and U.S. energy policy attempts to increase the penetration of renewable energy. However, renewable energy technologies (R_t=1) with the exception of biodiesel, biomass, and geothermal (heat pump) are not dispatchable (P_t=0) [9]. This means that they are not capable of generating energy according to the end-user demand fluctuation. Thus, dispatchability and renewable penetration constraints often conflict. Figure 4 gives the schematic of the two-stage framework.

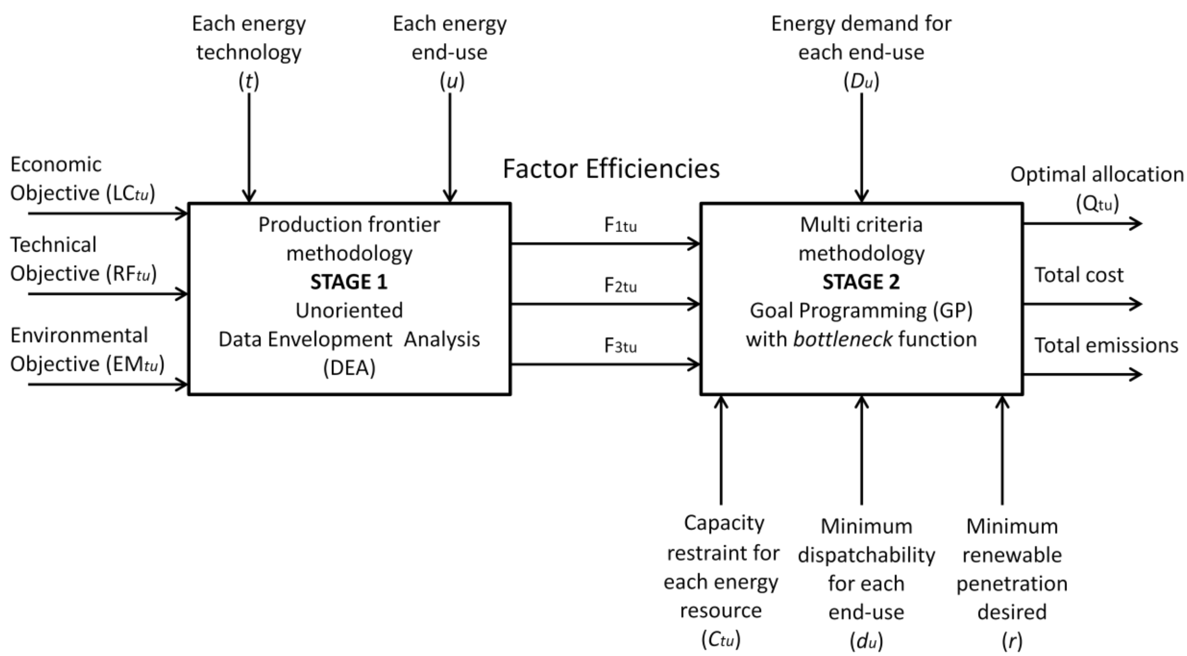


Figure 4. The Two-Stage DER Technology-Policy Framework

Chapter 5

Demonstration of the Framework

We first apply the first stage DEA model to find factor efficiencies of energy technologies. We carry forward the first stage results to the second stage. The second stage consists of a goal programming model which considers various energy consumer inputs and finds the Pareto-optimal energy technology and end-use allocation for that user.

5.1. Data and Results for the First Stage

In the first stage of the framework, we begin by calculating the efficiency scores of each energy technology within an end-use by applying the unoriented DEA model for each end-use individually. Next, we determine the factor efficiency scores by using actual and target levels of LC, RF, and EM for all energy technologies within all end-uses. Tables 5a to 5h show the technology efficiency scores, actual values, target values, and factor efficiencies for all the energy technologies used for all the end-uses.

For water pumping end-use u =1													
Energy Technology	t	k	Efficiency Scores		Economic Objective LC (cents/kWh)			Technical Objective RF (ratio)			Environment Objective EM (grams/kWh)		
			ε_k	θ_k	Actual	Target	Factor Efficiency Score (F_{1t1})	Actual	Target	Factor Efficiency Score (F_{2t1})	Actual	Target	Factor Efficiency Score (F_{3t1})
Grid electricity	1	1	0.56	1.44	16.50	9.19	0.5568	93.00	100.00	0.9300	337.65	188.00	0.5568
Grid electricity with battery storage	2	2	0.45	1.55	26.71	12.08	0.4524	98.00	100.00	0.9800	419.86	189.96	0.4524
Grid electricity with pumped water storage	3	3	0.47	1.53	22.61	10.56	0.4670	99.00	100.00	0.9900	450.20	210.26	0.4670
Grid electricity with compressed air storage	4	4	0.42	1.58	24.81	10.36	0.4176	97.00	100.00	0.9700	519.46	216.95	0.4176
Grid electricity with hydrogen generation	5	5	0.57	1.43	14.21	8.05	0.5667	99.00	100.00	0.9900	964.72	232.98	0.2415
Diesel engine electricity	6	6	0.63	1.37	10.48	6.64	0.6333	85.00	100.00	0.8500	298.54	189.07	0.6333
Diesel engine CHP	7	7	0.87	1.13	6.26	5.46	0.8727	85.00	95.82	0.8871	179.12	156.32	0.8727
Diesel engine CCHP	8	8	0.83	1.17	7.35	6.11	0.8304	85.00	99.42	0.8550	179.12	148.74	0.8304
Biodiesel-B100 engine electricity	9	9	0.69	1.31	11.07	7.69	0.6947	84.00	100.00	0.8400	217.45	151.07	0.6947
Biodiesel-B100 engine CHP	10	10	0.93	1.07	6.79	6.29	0.9268	84.00	90.15	0.9318	134.50	124.65	0.9268
Biodiesel-B100 engine CCHP	11	11	0.89	1.11	7.91	7.08	0.8945	84.00	92.86	0.9046	134.50	120.31	0.8945
Gas engine electricity	12	12	0.71	1.29	10.48	7.46	0.7114	88.00	100.00	0.8800	229.13	163.00	0.7114
Gas engine CHP	13	13	0.98	1.02	6.05	5.91	0.9763	88.00	90.08	0.9769	132.83	129.69	0.9763
Gas engine CCHP	14	14	0.94	1.06	7.10	6.71	0.9442	88.00	92.91	0.9471	132.83	125.42	0.9442
Gas turbine electricity	15	15	0.71	1.29	10.55	7.45	0.7060	90.00	100.00	0.9000	241.07	170.21	0.7060
Gas turbine CHP	16	16	1.00	1.00	5.42	5.42	1.0000	90.00	90.00	1.0000	136.08	136.08	1.0000
Gas turbine CCHP	17	17	0.97	1.03	6.45	6.24	0.9678	90.00	92.90	0.9688	136.08	131.71	0.9678
Gas microturbine electricity	18	18	0.61	1.39	11.56	7.00	0.6056	88.00	100.00	0.8800	330.36	200.07	0.6056
Gas microturbine CHP	19	19	1.00	1.00	4.99	4.99	1.0000	88.00	88.00	1.0000	144.48	144.48	1.0000
Gas microturbine CCHP	20	20	0.98	1.02	5.39	5.27	0.9781	88.00	89.93	0.9786	144.48	141.32	0.9781
Biomass-direct electricity	21	21	0.61	1.39	12.31	7.49	0.6088	80.00	100.00	0.8000	258.87	157.59	0.6088
Biomass-direct CHP	22	22	0.89	1.11	6.66	5.92	0.8895	80.00	88.84	0.9005	142.38	126.64	0.8895
Biomass-direct CCHP	23	23	0.86	1.14	7.66	6.60	0.8616	80.00	91.07	0.8784	142.38	122.67	0.8616
Polymer electrolyte membrane fuel cells electricity	24	24	0.64	1.36	16.75	10.73	0.6407	96.00	100.00	0.9600	253.27	162.27	0.6407
Polymer electrolyte membrane fuel cells CHP	25	25	0.94	1.06	9.11	8.53	0.9354	96.00	100.00	0.9600	135.43	126.67	0.9354
Phosphoric acid fuel cells electricity	26	26	0.71	1.29	16.68	11.78	0.7060	96.00	100.00	0.9600	211.05	149.00	0.7060
Phosphoric acid fuel cells CHP	27	27	1.00	1.00	7.61	7.61	1.0000	96.00	96.00	1.0000	120.38	120.38	1.0000
Molten carbonated fuel cells electricity	28	28	0.79	1.21	17.75	14.09	0.7938	96.00	100.00	0.9600	161.17	127.93	0.7938
Molten carbonated fuel cells CHP	29	29	0.83	1.17	13.70	11.43	0.8347	96.00	100.00	0.9600	157.27	131.27	0.8347
Solid oxide fuel cells electricity	30	30	0.83	1.17	18.81	15.52	0.8251	98.00	100.00	0.9800	147.74	121.90	0.8251
Solid oxide fuel cells CHP	31	31	0.95	1.05	11.62	10.99	0.9456	98.00	100.00	0.9800	126.63	119.74	0.9456
Wind turbine- onshore electricity	32	32	1.00	1.00	15.69	15.69	1.0000	36.00	36.00	1.0000	0.00	0.00	1.0000
Solar photovoltaic-thin film electricity	33	33	0.60	1.40	23.66	14.08	0.5952	23.00	32.31	0.7118	0.00	0.00	1.0000
Solar photovoltaic- crystalline electricity	34	34	0.63	1.37	25.48	16.10	0.6319	27.00	36.94	0.7309	0.00	0.00	1.0000
Parabolic trough solar thermal electricity	35	35	0.64	1.36	26.78	17.17	0.6413	29.00	39.40	0.7360	0.00	0.00	1.0000
Central receiver solar thermal electricity	36	36	0.86	1.14	21.97	18.89	0.8596	38.00	43.33	0.8769	0.00	0.00	1.0000

Table 5a. First Stage Results for Water Pumping End-Use

For water heating end-use u=2														
Energy Technology	t	k	Efficiency Scores		Economic Objective LC (cents/kWh)			Technical Objective RF (ratio)			Environment Objective EM (grams/kWh)		
			ε_k	θ_k	Actual	Target	Factor Efficiency	Actual	Target	Factor Efficiency	Actual	Target	Factor Efficiency
Grid electricity	1	1	0.42	1.58	16.50	6.91	0.4190	93.00	147.03	0.9300	210.17	88.06	0.4190
Grid electricity with battery storage	2	2	0.34	1.66	26.71	9.05	0.3389	98.00	162.79	0.9800	247.26	83.78	0.3389
Grid electricity with pumped water storage	3	3	0.35	1.65	22.61	7.82	0.3458	99.00	163.76	0.9900	280.23	96.91	0.3458
Grid electricity with compressed air storage	4	4	0.32	1.68	24.81	7.89	0.3181	97.00	163.14	0.9700	300.24	95.52	0.3181
Grid electricity with hydrogen generation	5	5	0.47	1.53	14.21	6.73	0.4736	99.00	151.11	0.9900	297.21	94.18	0.3169
Diesel engine electricity	6	6	0.53	1.47	10.48	5.56	0.5307	85.00	124.89	0.8500	185.83	77.84	0.4189
Diesel engine CHP	7	7	0.84	1.16	5.22	4.39	0.8409	85.00	98.52	0.8627	91.05	61.41	0.6744
Diesel engine CCHP	8	8	0.76	1.24	6.13	4.68	0.7638	85.00	105.08	0.8500	91.05	65.49	0.7192
Biodiesel-B100 engine electricity	9	9	0.53	1.47	11.07	5.92	0.5348	84.00	123.07	0.8400	135.35	72.39	0.5348
Biodiesel-B100 engine CHP	10	10	0.87	1.13	5.28	4.60	0.8699	84.00	94.93	0.8849	63.87	55.55	0.8699
Biodiesel-B100 engine CCHP	11	11	0.83	1.17	6.16	5.14	0.8348	84.00	97.87	0.8583	63.87	53.32	0.8348
Gas engine electricity	12	12	0.55	1.45	10.48	5.77	0.5509	88.00	127.53	0.8800	142.62	78.56	0.5509
Gas engine CHP	13	13	0.85	1.15	5.43	4.62	0.8509	88.00	101.12	0.8800	72.72	61.88	0.8509
Gas engine CCHP	14	14	0.82	1.18	6.38	5.20	0.8164	88.00	104.16	0.8800	72.72	59.36	0.8164
Gas turbine electricity	15	15	0.55	1.45	10.55	5.81	0.5506	90.00	130.44	0.9000	150.06	81.30	0.5418
Gas turbine CHP	16	16	0.88	1.12	5.13	4.50	0.8774	90.00	101.03	0.9000	78.52	62.97	0.8019
Gas turbine CCHP	17	17	0.82	1.18	6.10	4.98	0.8162	90.00	106.54	0.9000	78.52	64.09	0.8162
Gas microturbine electricity	18	18	0.51	1.49	11.56	5.85	0.5064	88.00	131.44	0.8800	205.63	81.92	0.3984
Gas microturbine CHP	19	19	0.68	1.32	7.57	5.16	0.6825	88.00	115.94	0.8800	133.54	72.26	0.5411
Gas microturbine CCHP	20	20	0.65	1.35	8.17	5.30	0.6484	88.00	118.94	0.8800	133.54	74.13	0.5551
Biomass-direct electricity	21	21	0.46	1.54	12.31	5.69	0.4626	80.00	123.00	0.8000	161.13	74.53	0.4626
Biomass-direct CHP	22	22	0.72	1.28	6.66	4.76	0.7159	80.00	102.73	0.8000	86.85	62.17	0.7159
Biomass-direct CCHP	23	23	0.69	1.31	7.66	5.26	0.6874	80.00	105.01	0.8000	86.85	59.70	0.6874
Polymer electrolyte membrane fuel cells electricity	24	24	0.48	1.52	16.75	8.05	0.4803	96.00	145.89	0.9600	157.64	75.72	0.4803
Polymer electrolyte membrane fuel cells CHP	25	25	0.93	1.07	4.96	4.59	0.9257	96.00	103.13	0.9600	89.11	64.28	0.7213
Phosphoric acid fuel cells electricity	26	26	0.51	1.49	16.68	8.56	0.5130	96.00	142.75	0.9600	131.37	67.39	0.5130
Phosphoric acid fuel cells CHP	27	27	0.64	1.36	11.07	7.10	0.6417	96.00	130.39	0.9600	106.81	68.54	0.6417
Molten carbonated fuel cells electricity	28	28	0.56	1.44	17.75	9.88	0.5565	96.00	138.57	0.9600	100.32	55.83	0.5565
Molten carbonated fuel cells CHP	29	29	1.00	1.00	6.05	6.05	1.0000	96.00	96.00	1.0000	42.39	42.39	1.0000
Solid oxide fuel cells electricity	30	30	0.57	1.43	18.81	10.77	0.5725	98.00	139.90	0.9800	91.96	52.64	0.5725
Solid oxide fuel cells CHP	31	31	0.82	1.18	9.19	7.53	0.8191	98.00	115.73	0.9800	61.08	50.03	0.8191
Wind turbine- onshore electricity	32	32	0.53	1.47	15.69	8.32	0.5303	36.00	52.91	0.6804	0.00	0.00	1.0000
Solar photovoltaic-thin film electricity	33	33	0.27	1.73	23.66	6.27	0.2652	23.00	39.90	0.5764	0.00	0.00	1.0000
Solar photovoltaic- crystalline electricity	34	34	0.29	1.71	25.48	7.28	0.2857	27.00	46.29	0.5833	0.00	0.00	1.0000
Parabolic trough solar thermal electricity	35	35	0.29	1.71	26.78	7.79	0.2910	29.00	49.56	0.5851	0.00	0.00	1.0000
Central receiver solar thermal electricity	36	36	0.43	1.57	21.97	9.40	0.4277	38.00	59.75	0.6360	0.00	0.00	1.0000
Solar thermal collector water heater	37	37	1.00	1.00	6.29	6.29	1.0000	40.00	40.00	1.0000	0.00	0.00	1.0000
Fuel oil water heater	40	38	0.87	1.13	5.45	4.76	0.8741	95.00	106.96	0.9500	102.42	66.66	0.6509
Gas water heater	41	39	1.00	1.00	4.32	4.32	1.0000	97.00	97.00	1.0000	60.46	60.46	1.0000
Biomass fired boiler	44	40	0.89	1.11	4.71	4.20	0.8912	85.00	94.25	0.9019	73.69	58.74	0.7971
Geothermal pump with desuperheater	46	41	0.99	1.01	7.21	7.13	0.9887	98.00	99.11	0.9888	40.09	39.64	0.9887

Table 5b. First Stage Results for Water Heating End-Use

For space heating end-use u=3													
Energy Technology	i	k	Efficiency Scores		Economic Objective LC (cents/kWh)			Technical Objective RF (ratio)			Environment Objective EM (grams/kWh)		
			ε_k	θ_k	Actual	Target	Factor Efficiency Score (F_{1k3})	Actual	Target	Factor Efficiency Score (F_{2k3})	Actual	Target	Factor Efficiency Score (F_{3k3})
Grid electricity	1	1	0.42	1.58	16.50	6.86	0.4159	93.00	100.00	0.9300	216.81	90.16	0.4159
Grid electricity with battery storage	2	2	0.31	1.69	26.71	8.29	0.3106	98.00	100.00	0.9800	271.01	84.16	0.3106
Grid electricity with pumped water storage	3	3	0.34	1.66	22.61	7.71	0.3411	99.00	100.00	0.9900	289.08	98.62	0.3411
Grid electricity with compressed air storage	4	4	0.31	1.69	24.81	7.60	0.3062	97.00	100.00	0.9700	333.55	102.15	0.3062
Grid electricity with hydrogen generation	5	5	0.47	1.53	14.21	6.68	0.4699	99.00	100.00	0.9900	619.45	103.83	0.1676
Diesel engine electricity	6	6	0.53	1.47	10.48	5.52	0.5267	85.00	100.00	0.8500	191.69	85.84	0.4478
Diesel engine CHP	7	7	0.84	1.16	5.22	4.36	0.8359	85.00	98.95	0.8590	91.05	67.82	0.7449
Diesel engine CCHP	8	8	0.77	1.23	6.13	4.69	0.7662	85.00	100.00	0.8500	91.05	69.77	0.7662
Biodiesel-B100 engine electricity	9	9	0.53	1.47	11.07	5.83	0.5271	84.00	100.00	0.8400	139.63	73.60	0.5271
Biodiesel-B100 engine CHP	10	10	0.86	1.14	5.28	4.56	0.8632	84.00	95.49	0.8797	63.87	55.13	0.8632
Biodiesel-B100 engine CCHP	11	11	0.81	1.19	6.16	4.98	0.8092	84.00	100.00	0.8400	63.87	51.68	0.8092
Gas engine electricity	12	12	0.55	1.45	10.48	5.80	0.5539	88.00	100.00	0.8800	147.13	81.49	0.5539
Gas engine CHP	13	13	0.86	1.14	5.43	4.66	0.8574	88.00	100.00	0.8800	72.72	62.35	0.8574
Gas engine CCHP	14	14	0.80	1.20	6.38	5.12	0.8025	88.00	100.00	0.8800	72.72	58.36	0.8025
Gas turbine electricity	15	15	0.55	1.45	10.55	5.85	0.5544	90.00	100.00	0.9000	154.79	85.82	0.5544
Gas turbine CHP	16	16	0.87	1.13	5.13	4.49	0.8750	90.00	100.00	0.9000	78.52	68.70	0.8750
Gas turbine CCHP	17	17	0.82	1.18	6.10	4.99	0.8176	90.00	100.00	0.9000	78.52	64.20	0.8176
Gas microturbine electricity	18	18	0.50	1.50	11.56	5.81	0.5025	88.00	100.00	0.8800	212.12	90.33	0.4258
Gas microturbine CHP	19	19	0.68	1.32	7.57	5.13	0.6779	88.00	100.00	0.8800	133.54	79.75	0.5972
Gas microturbine CCHP	20	20	0.64	1.36	8.17	5.26	0.6440	88.00	100.00	0.8800	133.54	81.79	0.6125
Biomass-direct electricity	21	21	0.46	1.54	12.31	5.68	0.4617	80.00	100.00	0.8000	166.22	76.74	0.4617
Biomass-direct CHP	22	22	0.72	1.28	6.66	4.78	0.7188	80.00	100.00	0.8000	86.85	62.43	0.7188
Biomass-direct CCHP	23	23	0.67	1.33	7.66	5.16	0.6739	80.00	100.00	0.8000	86.85	58.53	0.6739
Polymer electrolyte membrane fuel cells electricity	24	24	0.45	1.55	16.75	7.54	0.4500	96.00	100.00	0.9600	162.62	73.19	0.4500
Polymer electrolyte membrane fuel cells CHP	25	25	0.92	1.08	4.96	4.57	0.9206	96.00	100.00	0.9600	87.33	71.03	0.8133
Phosphoric acid fuel cells electricity	26	26	0.47	1.53	16.68	7.77	0.4661	96.00	100.00	0.9600	135.52	63.17	0.4661
Phosphoric acid fuel cells CHP	27	27	0.61	1.39	11.07	6.76	0.6111	96.00	100.00	0.9600	106.81	65.27	0.6111
Molten carbonated fuel cells electricity	28	28	0.47	1.53	17.75	8.28	0.4664	96.00	100.00	0.9600	103.49	48.27	0.4664
Molten carbonated fuel cells CHP	29	29	0.93	1.07	6.05	5.61	0.9266	96.00	100.00	0.9600	42.39	39.28	0.9266
Solid oxide fuel cells electricity	30	30	0.46	1.54	18.81	8.67	0.4611	98.00	100.00	0.9800	94.86	43.75	0.4611
Solid oxide fuel cells CHP	31	31	0.74	1.26	9.19	6.79	0.7391	98.00	100.00	0.9800	61.08	45.14	0.7391
Wind turbine- onshore electricity	32	32	0.64	1.36	15.69	10.11	0.6445	36.00	48.80	0.7378	0.00	0.00	1.0000
Solar photovoltaic-thin film electricity	33	33	0.34	1.66	23.66	7.93	0.3354	20.00	38.29	0.5224	0.00	0.00	1.0000
Solar photovoltaic- crystalline electricity	34	34	0.36	1.64	25.48	9.18	0.3601	23.00	44.28	0.5195	0.00	0.00	1.0000
Parabolic trough solar thermal electricity	35	35	0.37	1.63	26.78	9.82	0.3666	25.00	47.37	0.5278	0.00	0.00	1.0000
Central receiver solar thermal electricity	36	36	0.53	1.47	21.97	11.59	0.5277	28.00	55.95	0.5005	0.00	0.00	1.0000
Solar thermal collector	38	37	1.00	1.00	6.01	6.01	1.0000	29.00	29.00	1.0000	0.00	0.00	1.0000
Oil-fired furnace / boiler	42	38	0.87	1.13	5.45	4.74	0.8690	95.00	100.00	0.9500	105.05	73.64	0.7011
Gas-fired furnace / boiler	43	39	1.00	1.00	4.32	4.32	1.0000	98.00	98.00	1.0000	67.17	67.17	1.0000
Biomass fired boiler	44	40	0.89	1.11	4.71	4.17	0.8861	85.00	94.68	0.8978	73.69	64.90	0.8807
Geothermal ground closed loop heat pump	45	41	1.00	1.00	5.81	5.81	1.0000	98.00	98.00	1.0000	23.33	23.33	1.0000

Table 5c. First Stage Results for Space Heating End-Use

For ventilation end-use u=4													
Energy Technology	t	k	Efficiency Scores		Economic Objective			Technical Objective			Environment Objective		
					LC (cents/kWh)			RF (ratio)			EM (grams/kWh)		
			ε_k	θ_k	Actual	Target	Factor Efficiency	Actual	Target	Factor Efficiency	Actual	Target	Factor Efficiency
Grid electricity	1	1	0.56	1.44	16.50	9.19	0.5568	93.00	134.22	0.9300	228.85	127.42	0.5568
Grid electricity with battery storage	2	2	0.45	1.55	26.71	12.04	0.4509	98.00	151.81	0.9800	286.06	129.00	0.4509
Grid electricity with pumped water storage	3	3	0.47	1.53	22.61	10.56	0.4670	99.00	151.76	0.9900	305.14	142.51	0.4670
Grid electricity with compressed air storage	4	4	0.42	1.58	24.81	10.36	0.4176	97.00	153.49	0.9700	352.08	147.05	0.4176
Grid electricity with hydrogen generation	5	5	0.57	1.43	14.21	8.05	0.5667	99.00	141.90	0.9900	653.86	157.91	0.2415
Diesel engine electricity	6	6	0.63	1.37	10.48	6.64	0.6333	85.00	116.17	0.8500	202.34	128.15	0.6333
Diesel engine CHP	7	7	0.87	1.13	6.26	5.46	0.8727	85.00	95.82	0.8871	121.41	105.95	0.8727
Diesel engine CCHP	8	8	0.83	1.17	7.35	6.11	0.8304	85.00	99.42	0.8550	121.41	100.81	0.8304
Biodiesel-B100 engine electricity	9	9	0.69	1.31	11.07	7.69	0.6947	84.00	109.64	0.8400	147.38	102.39	0.6947
Biodiesel-B100 engine CHP	10	10	0.93	1.07	6.79	6.29	0.9268	84.00	90.15	0.9318	91.16	84.49	0.9268
Biodiesel-B100 engine CCHP	11	11	0.89	1.11	7.91	7.08	0.8945	84.00	92.86	0.9046	91.16	81.54	0.8945
Gas engine electricity	12	12	0.71	1.29	10.48	7.46	0.7114	88.00	113.40	0.8800	155.30	110.48	0.7114
Gas engine CHP	13	13	0.98	1.02	6.05	5.91	0.9763	88.00	90.08	0.9769	90.03	87.90	0.9763
Gas engine CCHP	14	14	0.94	1.06	7.10	6.71	0.9442	88.00	92.91	0.9471	90.03	85.01	0.9442
Gas turbine electricity	15	15	0.71	1.29	10.55	7.45	0.7060	90.00	116.46	0.9000	163.39	115.36	0.7060
Gas turbine CHP	16	16	1.00	1.00	5.42	5.42	1.0000	90.00	90.00	1.0000	92.23	92.23	1.0000
Gas turbine CCHP	17	17	0.97	1.03	6.45	6.24	0.9678	90.00	92.90	0.9688	92.23	89.27	0.9678
Gas microturbine electricity	18	18	0.61	1.39	11.56	7.00	0.6056	88.00	122.71	0.8800	223.91	135.60	0.6056
Gas microturbine CHP	19	19	1.00	1.00	4.99	4.99	1.0000	88.00	88.00	1.0000	97.93	97.93	1.0000
Gas microturbine CCHP	20	20	0.98	1.02	5.39	5.27	0.9781	88.00	89.93	0.9786	97.93	95.78	0.9781
Biomass-direct electricity	21	21	0.61	1.39	12.31	7.49	0.6088	80.00	111.30	0.8000	175.45	106.81	0.6088
Biomass-direct CHP	22	22	0.89	1.11	6.66	5.92	0.8895	80.00	88.84	0.9005	96.50	85.83	0.8895
Biomass-direct CCHP	23	23	0.86	1.14	7.66	6.60	0.8616	80.00	91.07	0.8784	96.50	83.14	0.8616
Polymer electrolyte membrane fuel cells electricity	24	24	0.64	1.36	16.75	10.73	0.6407	96.00	130.49	0.9600	171.66	109.98	0.6407
Polymer electrolyte membrane fuel cells CHP	25	25	0.94	1.06	9.11	8.53	0.9354	96.00	102.21	0.9600	91.79	85.86	0.9354
Phosphoric acid fuel cells electricity	26	26	0.71	1.29	16.68	11.78	0.7060	96.00	124.23	0.9600	143.05	100.99	0.7060
Phosphoric acid fuel cells CHP	27	27	1.00	1.00	7.61	7.61	1.0000	96.00	96.00	1.0000	81.59	81.59	1.0000
Molten carbonated fuel cells electricity	28	28	0.79	1.21	17.75	14.09	0.7938	96.00	115.80	0.9600	109.24	86.71	0.7938
Molten carbonated fuel cells CHP	29	29	0.83	1.17	13.70	11.43	0.8347	96.00	111.87	0.9600	106.59	88.97	0.8347
Solid oxide fuel cells electricity	30	30	0.83	1.17	18.81	15.52	0.8251	98.00	115.14	0.9800	100.13	82.62	0.8251
Solid oxide fuel cells CHP	31	31	0.95	1.05	11.62	10.99	0.9456	98.00	103.33	0.9800	85.83	81.16	0.9456
Wind turbine- onshore electricity	32	32	1.00	1.00	15.69	15.69	1.0000	36.00	36.00	1.0000	0.00	0.00	1.0000
Solar photovoltaic-thin film electricity	33	33	0.60	1.40	23.66	14.08	0.5952	23.00	32.31	0.7118	0.00	0.00	1.0000
Solar photovoltaic- crystalline electricity	34	34	0.63	1.37	25.48	16.10	0.6319	27.00	36.94	0.7309	0.00	0.00	1.0000
Parabolic trough solar thermal electricity	35	35	0.64	1.36	26.78	17.17	0.6413	29.00	39.40	0.7360	0.00	0.00	1.0000
Central receiver solar thermal electricity	36	36	0.86	1.14	21.97	18.89	0.8596	38.00	43.33	0.8769	0.00	0.00	1.0000

Table 5d. First Stage Results for Ventilation End-Use

For space cooling end-use u=5													
Energy Technology	t	k	Efficiency Scores		Economic Objective LC (cents/kWh)			Technical Objective RF (ratio)			Environment Objective EM (grams/kWh)		
			ε_k	θ_k	Actual	Target	Factor Efficiency	Actual	Target	Factor Efficiency	Actual	Target	Factor Efficiency
Grid electricity	1	1	0.49	1.51	16.50	8.16	0.4947	93.00	140.00	0.9300	337.65	167.02	0.4947
Grid electricity with battery storage	2	2	0.36	1.64	26.71	9.53	0.3569	98.00	161.03	0.9800	422.06	150.61	0.3569
Grid electricity with pumped water storage	3	3	0.41	1.59	22.61	9.21	0.4073	99.00	157.68	0.9900	450.20	183.37	0.4073
Grid electricity with compressed air storage	4	4	0.37	1.63	24.81	9.20	0.3708	97.00	158.03	0.9700	519.46	192.61	0.3708
Grid electricity with hydrogen generation	5	5	0.57	1.43	14.21	8.05	0.5667	99.00	141.90	0.9900	964.72	232.98	0.2415
Diesel engine electricity	6	6	0.63	1.37	10.48	6.61	0.6310	85.00	116.37	0.8500	298.54	188.37	0.6310
Diesel engine CHP	7	7	0.87	1.13	6.26	5.45	0.8708	85.00	95.99	0.8855	179.12	155.97	0.8708
Diesel engine CCHP	8	8	0.90	1.10	6.13	5.50	0.8970	85.00	93.76	0.9066	115.02	103.17	0.8970
Biodiesel-B100 engine electricity	9	9	0.61	1.39	11.07	6.80	0.6145	84.00	116.38	0.8400	217.45	133.63	0.6145
Biodiesel-B100 engine CHP	10	10	0.84	1.16	6.79	5.70	0.8393	84.00	97.50	0.8615	134.50	112.88	0.8393
Biodiesel-B100 engine CCHP	11	11	0.90	1.10	6.16	5.52	0.8963	84.00	92.71	0.9060	86.36	77.41	0.8963
Gas engine electricity	12	12	0.66	1.34	10.48	6.87	0.6553	88.00	118.33	0.8800	229.13	150.15	0.6553
Gas engine CHP	13	13	0.92	1.08	6.05	5.54	0.9153	88.00	95.45	0.9219	132.83	121.59	0.9153
Gas engine CCHP	14	14	0.90	1.10	6.38	5.76	0.9032	88.00	96.52	0.9118	85.29	77.04	0.9032
Gas turbine electricity	15	15	0.66	1.34	10.55	6.97	0.6609	90.00	120.52	0.9000	241.07	159.32	0.6609
Gas turbine CHP	16	16	0.98	1.02	5.42	5.29	0.9762	90.00	92.14	0.9768	136.08	132.85	0.9762
Gas turbine CCHP	17	17	0.93	1.07	6.10	5.70	0.9347	90.00	95.87	0.9387	87.38	81.68	0.9347
Gas microturbine electricity	18	18	0.60	1.40	11.56	6.98	0.6038	88.00	122.86	0.8800	330.36	199.47	0.6038
Gas microturbine CHP	19	19	1.00	1.00	4.99	4.99	1.0000	88.00	88.00	1.0000	144.48	144.48	1.0000
Gas microturbine CCHP	20	20	0.79	1.21	8.17	6.42	0.7857	88.00	106.85	0.8800	92.77	72.90	0.7857
Biomass-direct electricity	21	21	0.55	1.45	12.31	6.76	0.5488	80.00	116.09	0.8000	258.87	142.07	0.5488
Biomass-direct CHP	22	22	0.82	1.18	6.66	5.47	0.8226	80.00	94.19	0.8494	142.38	117.13	0.8226
Biomass-direct CCHP	23	23	0.77	1.23	7.66	5.90	0.7704	80.00	98.37	0.8133	91.42	70.43	0.7704
Polymer electrolyte membrane fuel cells electrici	24	24	0.51	1.49	16.75	8.50	0.5075	96.00	143.28	0.9600	253.27	128.53	0.5075
Polymer electrolyte membrane fuel cells CHP	25	25	0.77	1.23	9.11	7.01	0.7695	96.00	118.13	0.9600	135.43	104.21	0.7695
Phosphoric acid fuel cells electricity	26	26	0.51	1.49	16.68	8.54	0.5122	96.00	142.83	0.9600	211.05	108.09	0.5122
Phosphoric acid fuel cells CHP	27	27	0.85	1.15	7.61	6.51	0.8549	96.00	109.93	0.9600	120.38	102.92	0.8549
Molten carbonated fuel cells electricity	28	28	0.49	1.51	17.75	8.76	0.4932	96.00	144.65	0.9600	161.17	79.50	0.4932
Molten carbonated fuel cells CHP	29	29	0.59	1.41	13.70	8.11	0.5924	96.00	135.13	0.9600	157.27	93.16	0.5924
Solid oxide fuel cells electricity	30	30	0.48	1.52	18.81	9.05	0.4810	98.00	148.86	0.9800	147.74	71.06	0.4810
Solid oxide fuel cells CHP	31	31	0.67	1.33	11.62	7.82	0.6731	98.00	130.03	0.9800	126.63	85.24	0.6731
Wind turbine- onshore electricity	32	32	0.52	1.48	15.69	8.21	0.5230	36.00	53.17	0.6770	0.00	0.00	1.0000
Solar photovoltaic-thin film electricity	33	33	0.26	1.74	23.66	6.17	0.2609	23.00	40.00	0.5750	0.00	0.00	1.0000
Solar photovoltaic- crystalline electricity	34	34	0.28	1.72	25.48	7.16	0.2811	27.00	46.41	0.5818	0.00	0.00	1.0000
Parabolic trough solar thermal electricity	35	35	0.29	1.71	26.78	7.67	0.2864	29.00	49.70	0.5836	0.00	0.00	1.0000
Central receiver solar thermal electricity	36	36	0.42	1.58	21.97	9.26	0.4214	38.00	59.99	0.6335	0.00	0.00	1.0000
Solar thermal collector	39	37	1.00	1.00	7.87	7.87	1.0000	51.00	51.00	1.0000	0.00	0.00	1.0000
Geothermal ground closed loop heat pump	45	38	1.00	1.00	5.85	5.85	1.0000	95.00	95.00	1.0000	23.33	23.33	1.0000

Table 5e. First Stage Results for Space Cooling End-Use

For refrigeration end-use u=6													
Energy Technology	t	k	Efficiency Scores		Economic Objective LC (cents/kWh)			Technical Objective RF (ratio)			Environment Objective EM (grams/kWh)		
			ε_k	θ_k	Actual	Target	Factor Efficiency	Actual	Target	Factor Efficiency	Actual	Target	Factor Efficiency
Grid electricity	1	1	0.56	1.44	16.50	9.19	0.5568	93.00	134.22	0.9300	502.36	279.71	0.5568
Grid electricity with battery storage	2	2	0.45	1.55	26.71	12.04	0.4509	98.00	151.81	0.9800	627.95	283.17	0.4509
Grid electricity with pumped water storage	3	3	0.47	1.53	22.61	10.56	0.4670	99.00	151.76	0.9900	669.81	312.82	0.4670
Grid electricity with compressed air storage	4	4	0.42	1.58	24.81	10.36	0.4176	97.00	153.49	0.9700	772.86	322.78	0.4176
Grid electricity with hydrogen generation	5	5	0.57	1.43	14.21	8.05	0.5667	99.00	141.90	0.9900	1435.31	346.62	0.2415
Diesel engine electricity	6	6	0.63	1.37	10.48	6.64	0.6333	85.00	116.17	0.8500	444.17	281.29	0.6333
Diesel engine CHP	7	7	0.87	1.13	6.26	5.46	0.8727	85.00	95.82	0.8871	266.50	232.57	0.8727
Diesel engine CCHP	8	8	0.83	1.17	7.35	6.11	0.8304	85.00	99.42	0.8550	266.50	221.30	0.8304
Biodiesel-B100 engine electricity	9	9	0.69	1.31	11.07	7.69	0.6947	84.00	109.64	0.8400	323.52	224.76	0.6947
Biodiesel-B100 engine CHP	10	10	0.93	1.07	6.79	6.29	0.9268	84.00	90.15	0.9318	200.10	185.46	0.9268
Biodiesel-B100 engine CCHP	11	11	0.89	1.11	7.91	7.08	0.8945	84.00	92.86	0.9046	200.10	178.99	0.8945
Gas engine electricity	12	12	0.71	1.29	10.48	7.46	0.7114	88.00	113.40	0.8800	340.90	242.51	0.7114
Gas engine CHP	13	13	0.98	1.02	6.05	5.91	0.9763	88.00	90.08	0.9769	197.63	192.95	0.9763
Gas engine CCHP	14	14	0.94	1.06	7.10	6.71	0.9442	88.00	92.91	0.9471	197.63	186.60	0.9442
Gas turbine electricity	15	15	0.71	1.29	10.55	7.45	0.7060	90.00	116.46	0.9000	358.67	253.24	0.7060
Gas turbine CHP	16	16	1.00	1.00	5.42	5.42	1.0000	90.00	90.00	1.0000	202.47	202.47	1.0000
Gas turbine CCHP	17	17	0.97	1.03	6.45	6.24	0.9678	90.00	92.90	0.9688	202.47	195.95	0.9678
Gas microturbine electricity	18	18	0.61	1.39	11.56	7.00	0.6056	88.00	122.71	0.8800	491.51	297.66	0.6056
Gas microturbine CHP	19	19	1.00	1.00	4.99	4.99	1.0000	88.00	88.00	1.0000	214.96	214.96	1.0000
Gas microturbine CCHP	20	20	0.98	1.02	5.39	5.27	0.9781	88.00	89.93	0.9786	214.96	210.25	0.9781
Biomass-direct electricity	21	21	0.61	1.39	12.31	7.49	0.6088	80.00	111.30	0.8000	385.14	234.46	0.6088
Biomass-direct CHP	22	22	0.89	1.11	6.66	5.92	0.8895	80.00	88.84	0.9005	211.83	188.41	0.8895
Biomass-direct CCHP	23	23	0.86	1.14	7.66	6.60	0.8616	80.00	91.07	0.8784	211.83	182.51	0.8616
Polymer electrolyte membrane fuel cells electricity	24	24	0.64	1.36	16.75	10.73	0.6407	96.00	130.49	0.9600	376.81	241.42	0.6407
Polymer electrolyte membrane fuel cells CHP	25	25	0.94	1.06	9.11	8.53	0.9354	96.00	102.21	0.9600	201.49	188.46	0.9354
Phosphoric acid fuel cells electricity	26	26	0.71	1.29	16.68	11.78	0.7060	96.00	124.23	0.9600	314.01	221.68	0.7060
Phosphoric acid fuel cells CHP	27	27	1.00	1.00	7.61	7.61	1.0000	96.00	96.00	1.0000	179.10	179.10	1.0000
Molten carbonated fuel cells electricity	28	28	0.79	1.21	17.75	14.09	0.7938	96.00	115.80	0.9600	239.79	190.34	0.7938
Molten carbonated fuel cells CHP	29	29	0.83	1.17	13.70	11.43	0.8347	96.00	111.87	0.9600	233.99	195.30	0.8347
Solid oxide fuel cells electricity	30	30	0.83	1.17	18.81	15.52	0.8251	98.00	115.14	0.9800	219.81	181.36	0.8251
Solid oxide fuel cells CHP	31	31	0.95	1.05	11.62	10.99	0.9456	98.00	103.33	0.9800	188.40	178.15	0.9456
Wind turbine- onshore electricity	32	32	1.00	1.00	15.69	15.69	1.0000	36.00	36.00	1.0000	0.00	0.00	1.0000
Solar photovoltaic-thin film electricity	33	33	0.60	1.40	23.66	14.08	0.5952	23.00	32.31	0.7118	0.00	0.00	1.0000
Solar photovoltaic- crystalline electricity	34	34	0.63	1.37	25.48	16.10	0.6319	27.00	36.94	0.7309	0.00	0.00	1.0000
Parabolic trough solar thermal electricity	35	35	0.64	1.36	26.78	17.17	0.6413	29.00	39.40	0.7360	0.00	0.00	1.0000
Central receiver solar thermal electricity	36	36	0.86	1.14	21.97	18.89	0.8596	38.00	43.33	0.8769	0.00	0.00	1.0000

Table 5f. First Stage Results for Refrigeration End-Use

For lighting end-use u=7													
Energy Technology	t	k	Efficiency Scores		Economic Objective LC (cents/kWh)			Technical Objective RF (ratio)			Environment Objective EM (grams/kWh)		
			ε_k	θ_k	Actual	Target	Factor Efficiency	Actual	Target	Factor Efficiency	Actual	Target	Factor Efficiency
Grid electricity	1	1	0.56	1.44	16.50	9.19	0.5568	93.00	134.22	0.9300	1317.76	733.73	0.5568
Grid electricity with battery storage	2	2	0.45	1.55	26.71	12.04	0.4509	98.00	151.81	0.9800	1647.21	742.79	0.4509
Grid electricity with pumped water storage	3	3	0.47	1.53	22.61	10.56	0.4670	99.00	151.76	0.9900	1757.02	820.58	0.4670
Grid electricity with compressed air storage	4	4	0.42	1.58	24.81	10.36	0.4176	97.00	153.49	0.9700	2027.33	846.71	0.4176
Grid electricity with hydrogen generation	5	5	0.57	1.43	14.21	8.05	0.5667	99.00	141.90	0.9900	3765.04	909.25	0.2415
Diesel engine electricity	6	6	0.63	1.37	10.48	6.64	0.6333	85.00	116.17	0.8500	1165.13	737.88	0.6333
Diesel engine CHP	7	7	0.87	1.13	6.26	5.46	0.8727	85.00	95.82	0.8871	699.08	610.08	0.8727
Diesel engine CCHP	8	8	0.83	1.17	7.35	6.11	0.8304	85.00	99.42	0.8550	699.08	580.50	0.8304
Biodiesel-B100 engine electricity	9	9	0.69	1.31	11.07	7.69	0.6947	84.00	109.64	0.8400	848.65	589.57	0.6947
Biodiesel-B100 engine CHP	10	10	0.93	1.07	6.79	6.29	0.9268	84.00	90.15	0.9318	524.91	486.49	0.9268
Biodiesel-B100 engine CCHP	11	11	0.89	1.11	7.91	7.08	0.8945	84.00	92.86	0.9046	524.91	469.53	0.8945
Gas engine electricity	12	12	0.71	1.29	10.48	7.46	0.7114	88.00	113.40	0.8800	894.24	636.14	0.7114
Gas engine CHP	13	13	0.98	1.02	6.05	5.91	0.9763	88.00	90.08	0.9769	518.42	506.15	0.9763
Gas engine CCHP	14	14	0.94	1.06	7.10	6.71	0.9442	88.00	92.91	0.9471	518.42	489.49	0.9442
Gas turbine electricity	15	15	0.71	1.29	10.55	7.45	0.7060	90.00	116.46	0.9000	940.84	664.28	0.7060
Gas turbine CHP	16	16	1.00	1.00	5.42	5.42	1.0000	90.00	90.00	1.0000	531.10	531.10	1.0000
Gas turbine CCHP	17	17	0.97	1.03	6.45	6.24	0.9678	90.00	92.90	0.9688	531.10	514.01	0.9678
Gas microturbine electricity	18	18	0.61	1.39	11.56	7.00	0.6056	88.00	122.71	0.8800	1289.31	780.81	0.6056
Gas microturbine CHP	19	19	1.00	1.00	4.99	4.99	1.0000	88.00	88.00	1.0000	563.88	563.88	1.0000
Gas microturbine CCHP	20	20	0.98	1.02	5.39	5.27	0.9781	88.00	89.93	0.9786	563.88	551.53	0.9781
Biomass-direct electricity	21	21	0.61	1.39	12.31	7.49	0.6088	80.00	111.30	0.8000	1010.29	615.03	0.6088
Biomass-direct CHP	22	22	0.89	1.11	6.66	5.92	0.8895	80.00	88.84	0.9005	555.66	494.24	0.8895
Biomass-direct CCHP	23	23	0.86	1.14	7.66	6.60	0.8616	80.00	91.07	0.8784	555.66	478.74	0.8616
Polymer electrolyte membrane fuel cells electricity	24	24	0.64	1.36	16.75	10.73	0.6407	96.00	130.49	0.9600	988.43	633.30	0.6407
Polymer electrolyte membrane fuel cells CHP	25	25	0.94	1.06	9.11	8.53	0.9354	96.00	102.21	0.9600	528.54	494.37	0.9354
Phosphoric acid fuel cells electricity	26	26	0.71	1.29	16.68	11.78	0.7060	96.00	124.23	0.9600	823.69	581.50	0.7060
Phosphoric acid fuel cells CHP	27	27	1.00	1.00	7.61	7.61	1.0000	96.00	96.00	1.0000	469.81	469.81	1.0000
Molten carbonated fuel cells electricity	28	28	0.79	1.21	17.75	14.09	0.7938	96.00	115.80	0.9600	629.00	499.30	0.7938
Molten carbonated fuel cells CHP	29	29	0.83	1.17	13.70	11.43	0.8347	96.00	111.87	0.9600	613.78	512.30	0.8347
Solid oxide fuel cells electricity	30	30	0.83	1.17	18.81	15.52	0.8251	98.00	115.14	0.9800	576.58	475.74	0.8251
Solid oxide fuel cells CHP	31	31	0.95	1.05	11.62	10.99	0.9456	98.00	103.33	0.9800	494.22	467.32	0.9456
Wind turbine- onshore electricity	32	32	1.00	1.00	15.69	15.69	1.0000	36.00	36.00	1.0000	0.00	0.00	1.0000
Solar photovoltaic-thin film electricity	33	33	0.60	1.40	23.66	14.08	0.5952	23.00	32.31	0.7118	0.00	0.00	1.0000
Solar photovoltaic- crystalline electricity	34	34	0.63	1.37	25.48	16.10	0.6319	27.00	36.94	0.7309	0.00	0.00	1.0000
Parabolic trough solar thermal electricity	35	35	0.64	1.36	26.78	17.17	0.6413	29.00	39.40	0.7360	0.00	0.00	1.0000
Central receiver solar thermal electricity	36	36	0.86	1.14	21.97	18.89	0.8596	38.00	43.33	0.8769	0.00	0.00	1.0000

Table 5g. First Stage Results for Lighting End-Use

For electronics and electricals end-use $u = 8$													
Energy Technology	t	k	Efficiency Scores		Economic Objective LC (cents/kWh)			Technical Objective RF (ratio)			Environment Objective EM (grams/kWh)		
			ε_k	θ_k	Actual	Target	Factor Efficiency	Actual	Target	Factor Efficiency	Actual	Target	Factor Efficiency
Grid electricity	1	1	0.56	1.44	16.50	9.19	0.5568	93.00	134.22	0.9300	286.06	159.28	0.5568
Grid electricity with battery storage	2	2	0.45	1.55	26.71	12.04	0.4509	98.00	151.81	0.9800	357.58	161.25	0.4509
Grid electricity with pumped water storage	3	3	0.47	1.53	22.61	10.56	0.4670	99.00	151.76	0.9900	381.42	178.13	0.4670
Grid electricity with compressed air storage	4	4	0.42	1.58	24.81	10.36	0.4176	97.00	153.49	0.9700	440.10	183.81	0.4176
Grid electricity with hydrogen generation	5	5	0.57	1.43	14.21	8.05	0.5667	99.00	141.90	0.9900	817.33	197.38	0.2415
Diesel engine electricity	6	6	0.63	1.37	10.48	6.64	0.6333	85.00	116.17	0.8500	252.93	160.18	0.6333
Diesel engine CHP	7	7	0.87	1.13	6.26	5.46	0.8727	85.00	95.82	0.8871	151.76	132.44	0.8727
Diesel engine CCHP	8	8	0.83	1.17	7.35	6.11	0.8304	85.00	99.42	0.8550	151.76	126.02	0.8304
Biodiesel-B100 engine electricity	9	9	0.69	1.31	11.07	7.69	0.6947	84.00	109.64	0.8400	184.23	127.99	0.6947
Biodiesel-B100 engine CHP	10	10	0.93	1.07	6.79	6.29	0.9268	84.00	90.15	0.9318	113.95	105.61	0.9268
Biodiesel-B100 engine CCHP	11	11	0.89	1.11	7.91	7.08	0.8945	84.00	92.86	0.9046	113.95	101.93	0.8945
Gas engine electricity	12	12	0.71	1.29	10.48	7.46	0.7114	88.00	113.40	0.8800	194.12	138.10	0.7114
Gas engine CHP	13	13	0.98	1.02	6.05	5.91	0.9763	88.00	90.08	0.9769	112.54	109.88	0.9763
Gas engine CCHP	14	14	0.94	1.06	7.10	6.71	0.9442	88.00	92.91	0.9471	112.54	106.26	0.9442
Gas turbine electricity	15	15	0.71	1.29	10.55	7.45	0.7060	90.00	116.46	0.9000	204.24	144.20	0.7060
Gas turbine CHP	16	16	1.00	1.00	5.42	5.42	1.0000	90.00	90.00	1.0000	115.29	115.29	1.0000
Gas turbine CCHP	17	17	0.97	1.03	6.45	6.24	0.9678	90.00	92.90	0.9688	115.29	111.58	0.9678
Gas microturbine electricity	18	18	0.61	1.39	11.56	7.00	0.6056	88.00	122.71	0.8800	279.89	169.50	0.6056
Gas microturbine CHP	19	19	1.00	1.00	4.99	4.99	1.0000	88.00	88.00	1.0000	122.41	122.41	1.0000
Gas microturbine CCHP	20	20	0.98	1.02	5.39	5.27	0.9781	88.00	89.93	0.9786	122.41	119.73	0.9781
Biomass-direct electricity	21	21	0.61	1.39	12.31	7.49	0.6088	80.00	111.30	0.8000	219.32	133.51	0.6088
Biomass-direct CHP	22	22	0.89	1.11	6.66	5.92	0.8895	80.00	88.84	0.9005	120.62	107.29	0.8895
Biomass-direct CCHP	23	23	0.86	1.14	7.66	6.60	0.8616	80.00	91.07	0.8784	120.62	103.93	0.8616
Polymer electrolyte membrane fuel cells electricity	24	24	0.64	1.36	16.75	10.73	0.6407	96.00	130.49	0.9600	214.57	137.48	0.6407
Polymer electrolyte membrane fuel cells CHP	25	25	0.94	1.06	9.11	8.53	0.9354	96.00	102.21	0.9600	114.74	107.32	0.9354
Phosphoric acid fuel cells electricity	26	26	0.71	1.29	16.68	11.78	0.7060	96.00	124.23	0.9600	178.81	126.23	0.7060
Phosphoric acid fuel cells CHP	27	27	1.00	1.00	7.61	7.61	1.0000	96.00	96.00	1.0000	101.99	101.99	1.0000
Molten carbonated fuel cells electricity	28	28	0.79	1.21	17.75	14.09	0.7938	96.00	115.80	0.9600	136.55	108.39	0.7938
Molten carbonated fuel cells CHP	29	29	0.83	1.17	13.70	11.43	0.8347	96.00	111.87	0.9600	133.24	111.21	0.8347
Solid oxide fuel cells electricity	30	30	0.83	1.17	18.81	15.52	0.8251	98.00	115.14	0.9800	125.17	103.28	0.8251
Solid oxide fuel cells CHP	31	31	0.95	1.05	11.62	10.99	0.9456	98.00	103.33	0.9800	107.29	101.45	0.9456
Wind turbine- onshore electricity	32	32	1.00	1.00	15.69	15.69	1.0000	36.00	36.00	1.0000	0.00	0.00	1.0000
Solar photovoltaic-thin film electricity	33	33	0.60	1.40	23.66	14.08	0.5952	23.00	32.31	0.7118	0.00	0.00	1.0000
Solar photovoltaic- crystalline electricity	34	34	0.63	1.37	25.48	16.10	0.6319	27.00	36.94	0.7309	0.00	0.00	1.0000
Parabolic trough solar thermal electricity	35	35	0.64	1.36	26.78	17.17	0.6413	29.00	39.40	0.7360	0.00	0.00	1.0000
Central receiver solar thermal electricity	36	36	0.86	1.14	21.97	18.89	0.8596	38.00	43.33	0.8769	0.00	0.00	1.0000

Table 5h. First Stage Results for Electronics and Electricals End-Use

The factor efficiency scores indicate the competitiveness for energy technologies and provide policy implications. For illustration (refer to Table 2c), the use of biomass fired boiler technology for space heating will become optimal if the LC is decreased by ¢0.54/kWh

(11.39%), RF is improved by 9.68 (10.22%), and EM is reduced by 8.79gram/kWh (11.93%) while the values for other technologies remain constant. To achieve the target values, LC can be reduced through incentives, RF can be improved through engineering design, and EM can be reduced through retrofitting devices such as carbon capture or sequester, catalysts, electrostatic precipitators, etc.

5.2. Data and Results for the Second Stage

In the second stage, we find the optimal energy allocation of energy technologies for various end-uses by applying the GP model. Table 6 gives the input data for the second stage. We find an optimal energy allocation for a typical commercial DER adopter whose total energy demand is about 100,000kWh for a defined demand period in the New York region [168]. We split the total energy demand into various end-use demands using approximate end-use energy demand percentages given for a commercial consumer in the Building Energy Data Book [141]. The percentages tend to be nearly constant as the defined demand periods (usually one year) are cyclical, hence the optimal allocation determined for a defined demand period can be generalized [141]. The end-use energy demand percentages vary by type of users (e.g. hospital, university, federal building, etc.) [141] [169]. This framework can be calibrated to any user by inputting their total energy demand for a year and respective end-use energy demand percentages obtained from the Building Energy Data Book. We assume minimum dispatchability and minimum renewable penetration percentages based on the Building Energy Data Book and the Annual Energy Outlook Report [141, 164]. Energy capacity is assumed as big M for all energy technologies. Table 7 tabulates the optimal energy allocation and related results.

	Water Pumping	Water Heating	Space Heating	Ventilation	Space Cooling	Refrigeration	Lighting	Electrical & Electronics	Total
Energy demand in kWh (D_u)	5000	7000	14000	6000	13000	4000	26000	25000	100000
Percent of total energy demand	0.05	0.07	0.14	0.06	0.13	0.04	0.26	0.25	1
Minimum dispatchable (d_u)	0.5	0.6	1	0.9	0.8	1	0.8	0.95	
Minimum renewable (r)	0.3								

Table 6. Input Data for Second Stage

i	P_i	R_i	u	1	2	3	4	5	6	7	8
			Q_{iu} (kWh)	Water pumping	Water heating	Space heating	Ventilation	Space cooling	Refrigeration	Lighting	Electricals and Electronics
1	1	0	Grid electricity	0	0	0	0	0	0	0	0
2	1	0	Grid electricity with battery storage	0	0	0	0	0	0	0	0
3	1	0	Grid electricity with pumped water storage	0	0	0	0	0	0	0	0
4	1	0	Grid electricity with compressed air storage	0	0	0	0	0	0	0	0
5	1	0	Grid electricity with hydrogen storage	0	0	0	0	0	0	0	0
6	1	0	Diesel engine electricity	0	0	0	0	0	0	0	0
7	1	0	Diesel engine CHP	0	0	0	0	0	0	0	0
8	1	0	Diesel engine CCHP	0	0	0	0	0	0	0	0
9	1	1	Biodiesel engine electricity	0	0	0	0	0	0	0	0
10	1	1	Biodiesel engine CHP	0	0	0	0	0	0	0	0
11	1	1	Biodiesel engine CCHP	0	0	0	0	0	0	0	0
12	1	0	Gas engine electricity	0	0	0	0	0	0	0	0
13	1	0	Gas engine CHP	0	0	0	0	0	0	0	0
14	1	0	Gas engine CCHP	0	0	0	0	0	0	0	0
15	1	0	Gas turbine electricity	0	0	0	0	0	0	0	0
16	1	0	Gas turbine CHP	2500	1860	6200	0	0	4000	96	0
17	1	0	Gas turbine CCHP	0	0	0	0	0	0	0	0
18	1	0	Gas microturbine electricity	0	0	0	0	0	0	0	0
19	1	0	Gas microturbine CHP	0	0	0	0	0	0	0	0
20	1	0	Gas microturbine CCHP	0	0	0	0	0	0	0	0
21	1	1	Biomass-direct electricity	0	0	0	0	0	0	0	0
22	1	1	Biomass-direct CHP	0	0	0	0	0	0	0	0
23	1	1	Biomass-direct CCHP	0	0	0	0	0	0	0	0
24	1	0	Polymer electrolyte membrane fuel cells electricity	0	0	0	0	0	0	0	0
25	1	0	Polymer electrolyte membrane fuel cells CHP	0	0	0	0	0	0	0	0
26	1	0	Phosphoric acid fuel cells electricity	0	0	0	0	0	0	0	0
27	1	0	Phosphoric acid fuel cells CHP	0	0	0	0	0	0	0	0
28	1	0	Molten carbonated fuel cells electricity	0	0	0	0	0	0	0	0
29	1	0	Molten carbonated fuel cells CHP	0	0	0	0	0	0	0	0
30	1	0	Solid oxide fuel cells electricity	0	0	0	5400	0	0	20704	23750
31	1	0	Solid oxide fuel cells CHP	0	0	0	0	0	0	0	0
32	0	1	Wind turbine- onshore electricity	2500	0	0	600	0	0	5200	1250
33	0	1	Solar photovoltaic-thin film electricity	0	0	0	0	0	0	0	0
34	0	1	Solar photovoltaic- crystalline electricity	0	0	0	0	0	0	0	0
35	0	1	Parabolic trough solar thermal electricity	0	0	0	0	0	0	0	0
36	0	1	Central receiver solar thermal electricity	0	0	0	0	0	0	0	0
37	0	1	Solar thermal collector water heater	0	2800	0	0	0	0	0	0
38	0	1	Solar thermal collector furnace	0	0	0	0	0	0	0	0
39	0	1	Solar thermal collector with adsorption chiller	0	0	0	0	2600	0	0	0
40	1	0	Fuel oil water heater	0	0	0	0	0	0	0	0
41	1	0	Gas water heater	0	0	0	0	0	0	0	0
42	1	0	Oil-fired furnace / boiler	0	0	0	0	0	0	0	0
43	1	0	Gas-fired furnace / boiler	0	0	0	0	0	0	0	0
44	1	1	Biomass fired boiler	0	0	0	0	0	0	0	0
45	1	1	Geothermal closed ground loop pump	0	0	7800	0	10400	0	0	0
46	1	1	Geothermal pump with desuperheater	0	2340	0	0	0	0	0	0
Total energy allocated (kWh)				5000	7000	14000	6000	13000	4000	26000	25000
Dispatchable energy percent				0.50	0.60	1.00	0.90	0.80	1.00	0.80	0.95
Total renewable energy percent				0.355							
Total energy levelized cost for demand period ($)				13258							
Total emissions for demand period (ton)				17.80							

Table 7. Optimal Energy Allocation Results

5.3. Interpretation of the Results

The optimal energy allocation in this scenario consists of seven technologies (highlighted), including one CHP technology. The electric energy from gas turbine with CHP technology (dispatchable) is used for water pumping, refrigeration, and a small amount for lighting. The dispatchable thermal energy that is captured through the cogeneration process is used for water heating and space heating.

Energy demand for water heating is constantly fulfilled by the geothermal desuperheater technology (dispatchable). In warm weather (>68°F), the geothermal pump functions as a reverse heat pump and releases less energy for water heating [162]. However during warm weather, solar energy is abundant and results in the dispatchability increase of the solar water heater, thus it can be used to fulfill the additional water heating demand. In cold weather (<32°F), water heating demand increases while the solar and the geothermal energy is inadequate to meet the demand. Thus, the dispatchable heat from the gas turbine CHP process is used to satisfy the surplus demand for water heating.

Energy demand for space heating increases in cold weather (<32°F) and geothermal pump technology cannot fulfill the demand. Hence the heat from the gas turbine CHP process is used to satisfy the surplus demand for space heating. Space heating is critical and hence all the energy supplied is dispatchable.

Similarly, energy demand for space cooling is satisfied by both solar thermal and geothermal pump technologies. In hot weather (>77°F), energy demand for space cooling increases and geothermal pump technology cannot fulfill the excess demand. Although during hot days, solar energy is abundant and the dispatchability of solar thermal collector with adsorption chiller technology increases, thus it can be used to satisfy the additional energy demand for space cooling.

Solid oxide fuel cell electricity is constantly used for pure electric needs— ventilation, lighting, and electrical and electronic end-uses. Adding a CHP system to fuel cell technology is expensive [170]. Due to high electric efficiency and low heat to power ratios, fuel cells are mostly suitable for electric needs only [117] [119]. The optimal energy allocation from the framework seems to reflect the same.

Wind power is suitable for energy demands that are capable of reducing the energy consumption when necessary [171]. Wind turbine electricity is not dispatchable and is used to satisfy half of water pumping demand, and a small portion of ventilation, lighting, and electrical and electronic demands. These end-uses are pure electric needs that do not mandate 100% dispatchability [1].

There are no slacks in the energy capacities and dispatchable energy. However, there is a positive slack of 5.5% for renewable energy penetration. The results suggest that the previously discussed technologies should be considered by the DER developer in this scenario. The grid electricity and storage technologies are not chosen for any end-use. The optimal energy allocation can alter when the cost, reliability, emissions, capacities for energy technologies, end-use energy demands, dispatchability of demands, or renewable penetration change. Table 8 shows the optimal energy percentages (both electric kWhe and thermal kWht) that should be planned through the selective energy technologies in this particular scenario.

Selected Energy Technologies	Energy %
Solid oxide fuel cells electricity	49.9
Geothermal ground loop heat pump	18.2
Gas turbine CHP	14.7
Wind turbine-onshore electricity	9.6
Solar thermal water heater	2.8
Solar thermal collector with adsorption chiller	2.6
Geothermal desuperheater	2.3

Table 8. Optimal Energy Percentages

5.4. Sensitivity Analysis

The policy variable – minimum renewable energy penetration (*r*) enables decision makers to examine the alteration of energy technology selection, optimal energy allocation, costs, and emissions by changing its value. The policy variable aims to determine policies that can encourage or discourage the DER stakeholders to consider certain renewable energy technologies depending on the end-uses, related energy demands, and dispatchability. To demonstrate this policy variable, we perform a sensitivity analysis by varying the renewable percentage from 0 to 100% in increments of 10%, while keeping other variables constant. We present the variation in the energy technology choice for the previously presented example. Table 9 tabulates the results and figure 5 graphically shows the patterns.

r %	0	10	20	30	40	50	60	70	80	90	100
Biodiesel-B100 engine electricity	0.0	0.0	0.0	0.0	0.0	0.0	8.4	18.4	28.4	38.4	48.4
Biodiesel-B100 engine CHP	0.0	0.0	0.0	0.0	2.0	12.9	16.1	16.1	16.1	16.1	16.1
Gas turbine CHP	14.7	14.7	14.7	14.7	8.3	0.0	0.0	0.0	0.0	0.0	0.0
Solid oxide fuel cells electricity	49.9	49.9	49.9	49.9	51.8	50.0	40.0	30.0	20.0	10.0	0.0
Wind turbine-onshore electricity	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6
Solar thermal water heater	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Solar thermal collector with adsorption chiller	2.6	2.6	2.6	2.6	0.0	1.0	2.6	2.6	2.6	2.6	2.6
Geothermal ground loop heat pump	18.2	18.2	18.2	18.2	22.8	21.1	18.2	18.2	18.2	18.2	18.2
Geothermal desuperheater	2.3	2.3	2.3	2.3	2.9	2.7	2.3	2.3	2.3	2.3	2.3
Total Levelized Cost ($)	13258	13258	13258	13258	13500	13358	12535	11761	10987	10213	9439
Total Emissions (tons)	17.80	17.80	17.80	17.80	17.74	17.66	18.40	18.93	19.69	22.41	23.09
Actual *r* achieved (%)	35.5	35.5	35.5	35.5	40.0	50.0	60.0	70.0	80.0	90.0	100.0

Table 9. Energy Technologies and Percentages for Different *r* Percentages

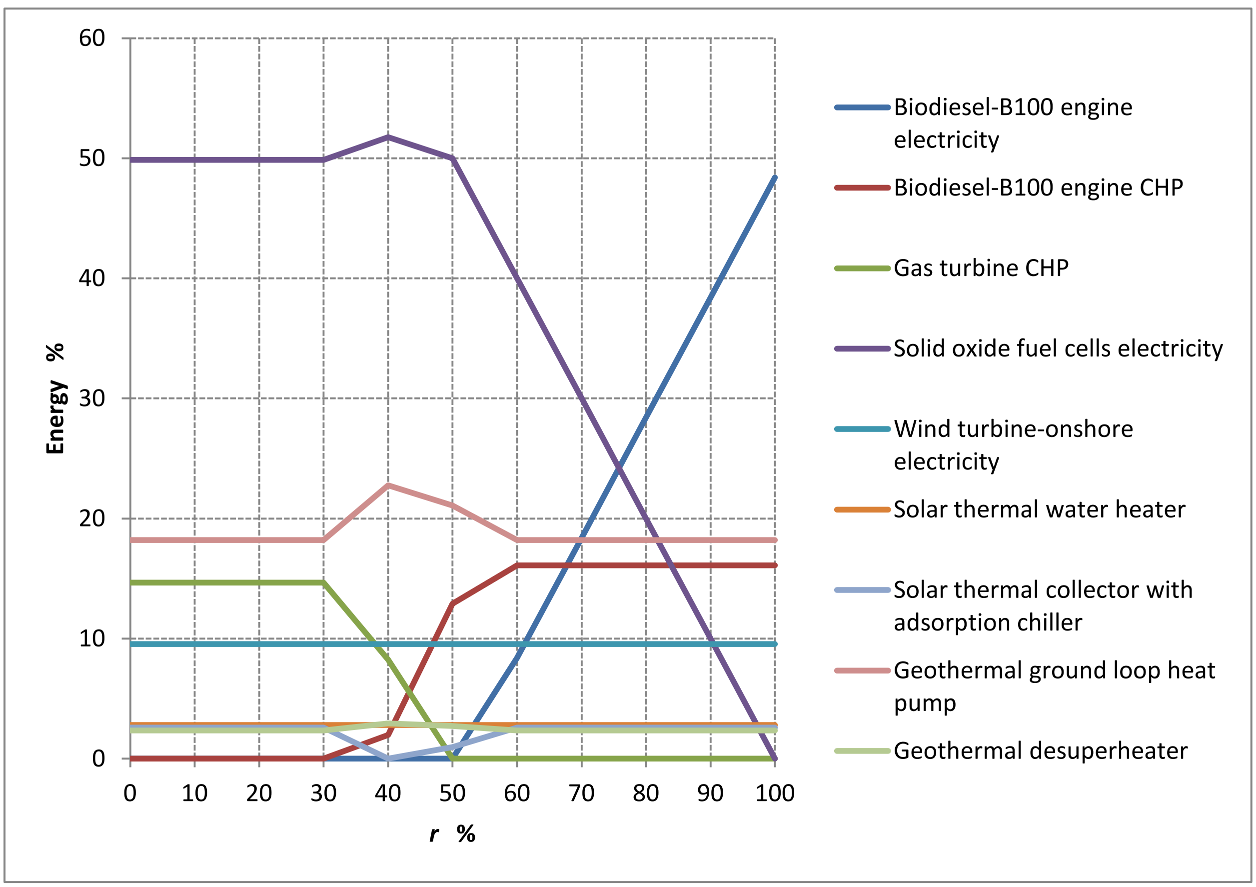


Figure 5. Energy Technologies trends

In this scenario, the optimal renewable energy percentage is 35.5%. When *r* approaches 40%, the natural gas turbine CHP energy declines steadily and the geothermal heat pump technology is chosen to compensate the energy supply gap. Beyond *r* = 40%, the use of biodiesel energy increases and fuel cells energy decreases as *r* % increases. In the group of energy technologies, the biodiesel engine is the only electric energy technology that uses renewable fuel and is dispatchable. Though biodiesel is a renewable fuel, the C emissions through energy generation are higher when compared to natural gas that is used by fuel cells energy technology [172]. On the other side, the cost of the biodiesel engine is less than that of fuel cells [173] . Thus, as *r* increases, the total emissions increase and the cost decrease while satisfying the minimum dispatchable energy demands. The highest cost and the lowest emissions happen at *r* =50%. Figure 6 shows the cost and emissions variation with respect to *r* %.

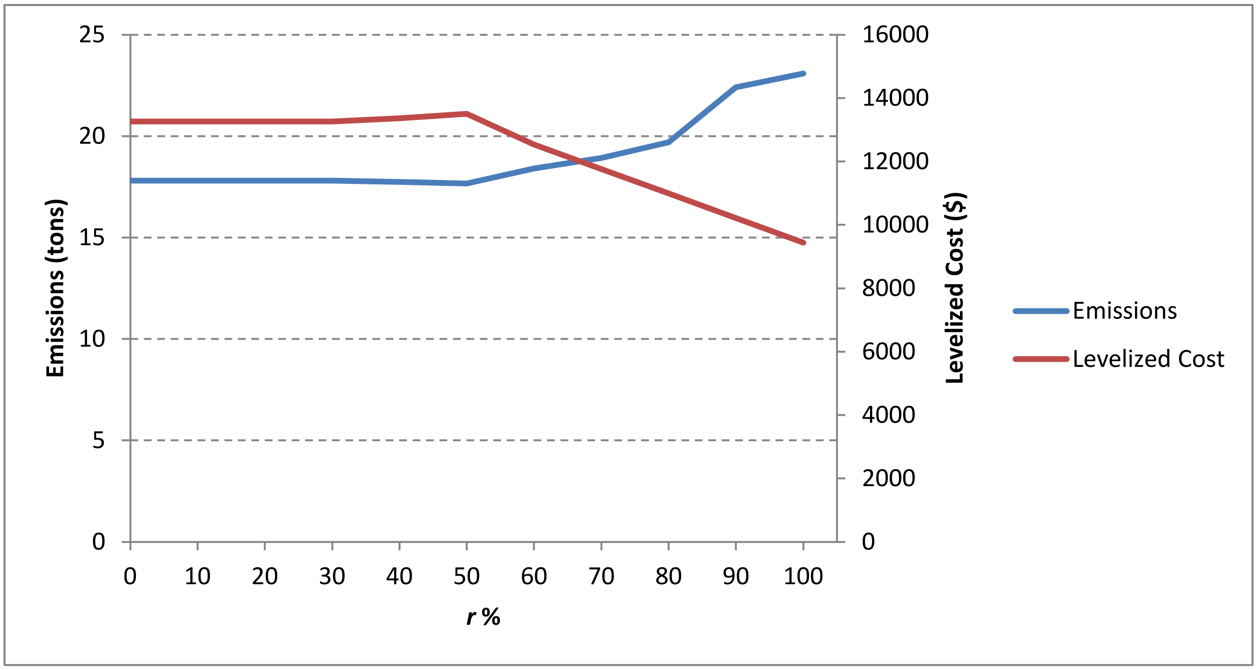


Figure 6. Changes in emissions and cost

We carry out different case studies to see the changes in energy technologies and energy capacities due to variation of other variables such as grid electric tariffs, local utility reliability, fuel source of local central power plant, local weather conditions, end-use energy splits, and respective dispatchability. The case studies are structured into categories – 1) different nature of users in a same region, and 2) same nature of users in different regions. The former one helps us understand the selection of energy technologies for different kinds of energy consumers and the latter one reveals the impact of regional differences in the choice of technologies. The next two chapters present the case studies

Chapter 6

Application to Large Energy Users in Different Regions

This chapter presents the case studies of a single type large energy user located in different regions in the US. The purpose of the case studies is to observe the variation in the selection of energy technologies and corresponding energy capacities due to change in the weather conditions and regional factors related to cost and energy availability. We choose university campuses with existing DER setup as a type of large energy user in different regions in the US [174].

University campuses are considered as mini cities because of their size, population, activities, buildings, and infrastructure network [175] . Universities are one of the major energy consumers in society [176]. Universities tend to have large floor spaces for classrooms, lecture halls, auditoriums, hallways, arenas, etc. that demand for large amounts of energy for heating, cooling, ventilation, and lighting needs [177]. The pollution caused by universities through energy generation and consumption could be reduced through a careful selection of energy technologies [169] by using a systematic and strategic framework [175].

We select four different regions in the US – Northeast, Midwest, South, and West which captures the diverse weather conditions of the US. The university campuses in these regions are selected upon availability of data from the respective institutions. We gather campus energy demands data from respective university *campus operations and maintenance* websites and personal communications. The following sub-sections present each case study.

6.1. South Region

The South region has a *humid subtropical climate* with hot summers and mild winters. The year-round weather is relatively warm i.e. there are more warmer days than colder days in an year [178]. For the South region, we study the *University of Texas* (UT) in Austin, Texas. Table 10 furnishes basic information of the campus along with the UT campus on-site primary energy resources.

University of Texas	
Location	Austin, Texas
Campus Type	Urban
Land Area	350 Acres
Number of Buildings	160
Floor Space	16,565,988 SqFt.
Number of Students	51145
Medical Center	No
Local Utility Power Plant Fuel Source	Natural Gas
Local Utility Tariff	11.4 Cents/kWh
On-Site DER Capacities	
Electric	140 MW
Technology	Natural Gas Turbines non-CHP
Heating	479,000 lbs of steam/hour
Technology	Natural Gas Boilers
Cooling	39,600 Tons
Technology	Electric Chillers

Table 10. UT Campus Information

UT uses three natural gas turbines to supply primary electric energy to the campus and six natural gas boilers to supply primary heat energy for water heating and space heating [179]. The campus uses electric energy from natural gas turbines and grid electricity for space cooling. Table 11 shows the energy demands for various campus end-uses in 2012 [180]. We calibrate the RF values of solar and wind, price of fuels, and local utility grid parameters for Austin, Texas and apply the model. Table 12 shows optimal DER allocation for UT.

	Water Pumping	Water Heating	Space Heating	Ventilation	Space Cooling	Refrigeration	Lighting	Electrical & Electronics
Approximate energy demand in kWh (D_u)	4,491,938	56,806,429	137,407,857	26,770,138	302,203,025	15,925,963	130,220,839	140,202,924
Approximate minimum dispatchable (d_u)	0.3	0.8	1	0.9	0.9	1	1	1

Table 11. UT Campus Approximate Energy Demands (in 2012)

% Energy (kWh)	Water pumping	Water heating	Space heating	Ventilation	Space cooling	Refrigeration	Lighting	Electricals and Electronics	Total Energy %
Natural gas microturbine electricity	-	-	-	-	29%	-	-	-	11%
Solid oxide fuel cells electricity	30%	-	-	90%	-	100%	100%	100%	38%
Wind turbine- onshore electricity	70%	-	-	10%	-	-	-	-	1%
Solar thermal collector water heater	-	20%	-	-	-	-	-	-	1%
Solar thermal collector with adsorption chiller	-	-	-	-	10%	-	-	-	4%
Gas water heater	-	7%	-	-	-	-	-	-	1%
Geothermal ground loop heat pump	-	-	100%	-	61%	-	-	-	39%
Geothermal pump with desuperheater	-	73%	-	-	-	-	-	-	5%

Table 12. Energy Allocation Results from Model Framework for UT Campus

The optimal energy allocation consists of eight technologies. There are no CHP technologies selected as the heating demands in Austin are relatively low. Solid oxide fuel cell electricity uses natural gas and can be constantly used for all electric end-uses. Solid oxide fuel cells posses the highest electric efficiency (60%) among all the energy technologies, making them ideal for electric needs only [117] [119].

Austin is suitable for generating solar and wind energy [164] [181]. In warm weather, solar energy is plentiful and thus solar water heaters can be used to fulfill the additional water heating demand. Primarily, energy demand for water heating can be fulfilled by the geothermal desuperheater technology. In cold weather (<32^{o}F), water heating demand increases while the solar and the geothermal energy is inadequate to meet the demand. However in Austin, the average temperature in winter tends to stay above 40^{o}F. Thus, only a small amount of dispatchable heat from the gas water heater is selected to satisfy the surplus demand for water heating in winter. Similarly, energy demand for space heating can be satisfied by the geothermal pump technology alone as the average winter temperatures usually stay around 40^{o}F in Austin [178].

The energy demand for space cooling can be satisfied by both solar thermal and geothermal pump technologies. In hot weather (>77^{o}F), energy demand for space cooling increases and the geothermal pump technology cannot fulfill the excess demand. During hot days in Austin, solar energy is abundant and solar thermal collector with adsorption chiller technology can be used to satisfy the additional energy demand for space cooling. The dispatchable electric energy from gas micro turbine technology can be used for space cooling in case of excessive cooling loads during the peak summer days when geothermal pumps are unable to keep up with the increased demand. A small portion of wind turbine electricity is chosen to satisfy reschedulable water pumping and ventilation demands. As the UT campus is located in the downtown, allocating land area for large wind turbines is not feasible.

6.2. Midwest Region

The Midwest region has a *humid continental climate* with harsh winters and severe humid summers. The year-round weather consists of both extreme hot and cold temperatures. For the Midwest region, we study the *University of Iowa* (UI) in Iowa City, Iowa. Table 13 furnishes basic information of the campus along with the campus on-site primary energy resources.

The University of Iowa	
Location	Iowa City, Iowa
Campus Type	Urban
Land Area	1900 Acres
Number of Buildings	513
Floor Space	14,777,352 SqFt.
Number of Students	31065
Medical Center	Yes
Local Utility Power Plant Fuel Source	Coal
Local Utility Tariff	10.5 Cents/kWh

On-Site DER Capacities	
Electric	25 MW
Technology	Coal/ Biomass Steam Turbines CHP
Heating	660,000 lbs of steam/hour
Technology	Coal/Biomass and Natural Gas Boilers
Cooling	45,950 Tons
Technology	Electric Chillers and Steam Turbine

Table 13. UI Campus Information

UI uses three coal powered steam turbine generators and grid electricity to supply primary electric energy to the campus. The UI campus is located near the *Quaker Oats®* factory and biomass is readily available in finite quantity from that facility for energy generation [182]. Thus, one of the three steam generators is retrofitted to use the available biomass as fuel. The campus uses cogeneration heat from the coal powered steam turbines, two natural gas boilers, one coal boiler, and one biomass boiler to supply heat energy for water heating and space heating. The campus uses electric energy from the steam turbines and grid electricity for space cooling. Table 14 shows the energy demands for various campus end-uses in 2012. We calibrate the RF values and cost of solar, wind, biomass, price of fuels, and local utility grid parameters for Iowa City, Iowa and apply the model. Table 15 shows optimal DER allocation for UI.

	Water Pumping	Water Heating	Space Heating	Ventilation	Space Cooling	Refrigeration	Lighting	Electrical & Electronics
Approximate energy demand in kWh (D_u)	13,768,160	125,729,563	440,053,471	80,314,269	208,467,532	68,840,802	217,995,874	103,261,203
Approximate minimum dispatchable (d_u)	0.78	0.95	1	0.95	0.87	1	0.95	1

Table 14. UI Campus Approximate Energy Demands (in 2012)

% Energy (kWh)	Water pumping	Water heating	Space heating	Ventilation	Space cooling	Refrigeration	Lighting	Electricals and Electronics	Total Energy %
Natural gas turbine CCHP	78%	69%	66%	95%	43%	100%	19%	100%	61%
Solid oxide fuel cells electricity	-	-	-	-	-	-	76%	-	13%
Wind turbine- onshore electricity	22%	-	-	5%	-	-	5%	-	1%
Biomass fired boiler	-	-	5%	-	-	-	-	-	2%
Geothermal ground loop heat pump	-	-	29%	-	57%	-	-	-	20%
Geothermal pump with desuperheater	-	31%	-	-	-	-	-	-	3%

Table 15. Energy Allocation Results from Model Framework for UI Campus

The optimal energy allocation consists of six technologies. There is a CCHP technology selected as both heating and cooling demands in Iowa City are relatively high. Heating, cooling and electricity from natural gas CCHP turbine technology is selected for heating, cooling, and electric energy demands, respectively. Solid oxide fuel cell electricity uses natural gas and is used for lighting demand.

Iowa City is highly suitable for generating wind energy [183] and biomass energy [184]. Thus, wind turbine electricity is selected to satisfy reschedulable water pumping, ventilation, and lighting demands. Biomass is finitely available near Iowa City (lowering the cost) due to various food products industries that produce biomass as a waste product (e.g. Quaker Oats). Thus, biomass boiler technology is selected for satisfying surplus heating demands in winter (<32^{o}F) whereas, primarily, heating can be fulfilled by geothermal pump technology and heat through gas turbine CCHP technology. Similarly, energy demand for water heating can be satisfied by geothermal desuperheater and residual heat from gas turbine CCHP technology. The energy demand for space cooling can be satisfied by both geothermal pump and chilled water from gas turbine CCHP technologies.

6.3. Northeast Region

The Northeast region has a combination of *humid subtropical climate* and *humid continental climate* with warm humid summers and long cold wet winters. The year-round weather is somewhat consists of a moderately sunny climate. For the Northeast region, we study *Stony Brook University* (SB) in Stony Brook, New York. Table 16 furnishes basic information of the campus along with the campus on-site primary energy resources.

Stony Brook University	
Location	Stony Brook, New York
Campus Type	Sub-Urban
Land Area	1394 Acres
Number of Buildings	162
Floor Space	12,127,398 SqFt.
Number of Students	24512
Medical Center	Yes
Local Utility Power Plant Fuel Source	Natural Gas
Local Utility Tariff	16.5 Cents/kWh

On-Site DER Capacities	
Electric	45 MW
Technology	Natural Gas Turbine CHP
Heating	360,000 lbs of steam/hour
Technology	Natural Gas and Fuel Oil Boilers
Cooling	45,950 Tons
Technology	Steam Chillers and Electric

Table 16. SB Campus Information

SB uses a natural gas CHP turbine and grid electricity to supply primary electric energy to the campus. The campus uses CHP heat from a natural gas turbine, and eight natural gas and fuel oil boilers to supply heat energy for water heating and space heating [185]. The campus uses cogeneration steam from the natural gas turbine, and electric energy from both the natural gas turbine and grid electricity for space cooling. Table 17 shows the energy demands for various campus end-uses in 2012. We calibrate the RF values and cost of solar and wind, price of fuels, and local utility grid parameters for Stony Brook, New York and apply the model. Table 18 shows optimal DER allocation for SB.

	Water Pumping	Water Heating	Space Heating	Ventilation	Space Cooling	Refrigeration	Lighting	Electrical & Electronics
Approximate energy demand in kWh (D_u)	2,564,341	94,250,000	282,750,000	42,739,023	213,880,422	34,191,218	136,764,872	102,573,654
Approximate minimum dispatchable (d_u)	0.7	0.9	1	0.95	0.95	1	1	1

Table 17. SB Campus Approximate Energy Demands (in 2012)

% Energy (kWh)	Water pumping	Water heating	Space heating	Ventilation	Space cooling	Refrigeration	Lighting	Electricals and Electronics	Total Energy %
Natural gas turbine CHP	70%	41%	46%	-	-	100%	75%	-	33.9%
Solid oxide fuel cells electricity	-	-	-	95%	15%	-	25%	100%	23.0%
Wind turbine- onshore electricity	30%	-	-	5%	-	-	-	-	0.3%
Solar Water Heater	-	10%	-	-	-	-	-	-	1.0%
Geothermal ground loop heat pump	-	-	54%	-	85%	-	-	-	36.7%
Geothermal pump with desuperheater	-	49%	-	-	-	-	-	-	5.0%

Table 18. Energy Allocation Results from Model Framework for SB Campus

The optimal energy allocation consists of six technologies. There is one CHP technology selected as heating demand is relatively higher than cooling demand. The heat and electricity from natural gas CHP turbine technology can be used for heating and electric energy demands, respectively. Solid oxide fuel cell electricity can be used for pure electric needs such as ventilation, lighting, and electrical equipment.

Long Island, New York is highly suitable for generating wind energy [186] and solar thermal energy [187]. Thus, wind turbine electricity is selected to satisfy small portion of reschedulable water pumping and ventilation demands. Water heating can be primarily fulfilled by thermal energy from natural gas CHP turbine and geothermal desuperheater. Solar energy can be used for the reschedulable portion of water heating. Geothermal pump technology in conjunction with cogeneration heat from the gas turbine can be used to satisfy the heating needs. Geothermal pump technology can be used to satisfy the regular cooling needs and Solid oxide fuel cell electricity is used to satisfy the surplus cooling needs during the peak summer days.

6.4. West Region

The West region has *Mediterranean climate* with mild dry summers and mild cold, rainy winters. The year-round weather consists of moderately sunny and foggy climate. For the West region, we study *Stanford University* (SF) in Stanford, California. Table 19 furnishes basic information of the campus along with the campus on-site primary energy resources.

Stanford University	
Location	Stanford, California
Campus Type	Sub-Urban
Land Area	8180 Acres
Number of Buildings	700
Floor Space	15,235,357 SqFt.
Number of Students	15877
Medical Center	Yes
Local Utility Power Plant Fuel Source	Natural Gas
Local Utility Tariff	15.2 Cents/kWh

On-Site DER Capacities	
Electric	42 MW
Technology	Natural Gas Turbine CHP
Heating	320,000 lbs of steam/hour
Technology	Natural Gas and Fuel Oil Boilers
Cooling	24,100 Tons
Technology	Electric Chillers and Steam

Table 19. SF Campus Information

SF uses a natural gas CHP turbine technology to supply primary electric energy to the campus. The campus uses CHP heat from the natural gas turbine, and four natural gas and fuel oil boilers to supply heat energy for water heating and space heating [188]. The campus uses cogeneration steam and electric energy from the natural gas turbine for space cooling [189]. Table 20 shows the energy demands for various campus end-uses in 2012. We calibrate the RF values and cost of solar and wind, price of fuels, and local utility grid parameters for Stanford, California and apply the model. Table 21 shows optimal DER allocation for SF.

	Water Pumping	Water Heating	Space Heating	Ventilation	Space Cooling	Refrigeration	Lighting	Electrical & Electronics
Approximate energy demand in kWh (D_u)	1,446,145	43,296,429	52,917,857	28,922,903	176,654,940	19,281,935	125,332,579	110,871,128
Approximate minimum dispatchable (d_u)	0.9	0.9	1	1	1	1	1	1

Table 20. SF Campus Approximate Energy Demands (in 2012)

% Energy (kWh)	Water pumping	Water heating	Space heating	Ventilation	Space cooling	Refrigeration	Lighting	Electricals and Electronics	Total Energy %
Natural gas turbine electricity	-	-	-	-	60%	-	-	-	19.0%
Solid oxide fuel cells electricity	90%	-	-	100%	-	100%	100%	100%	51.1%
Central receiver solar thermal electricity	10%	-	-	-	-	-	-	-	0.03%
Gas Water Heater	-	53%	-	-	-	-	-	-	4.1%
Solar Water Heater	-	10%	-	-	-	-	-	-	0.8%
Geothermal ground loop heat pump	-	-	100%	-	40%	-	-	-	22.1%
Geothermal pump with desuperheater	-	37%	-	-	-	-	-	-	2.8%

Table 21. Energy Allocation Results from Model Framework for SF Campus

The optimal energy allocation consists of seven technologies. There is no CHP technology selected as heating demand is relatively lower than cooling demand. The electricity from natural gas turbine technology can be used for cooling needs in summer. The high efficiency solid oxide fuel cell technology can be used for pure electric needs – water pumping, ventilation, refrigeration, lighting, and electronics.

Stanford, California is highly suitable for generating solar thermal energy [187]. Thus, solar electricity is selected to satisfy a small portion of the reschedulable water pumping. Solar water heater technology can be used for the reschedulable portion of water heating. Water heating can be primarily fulfilled by both gas water heater and geothermal desuperheater technologies.

Geothermal pump technology can fulfill the heating needs as the temperatures in California tend to stay around 40°F in winter. Geothermal pump technology can satisfy the regular cooling needs and gas turbine electricity can satisfy the surplus cooling needs during the peak summer days.

6.5. Summary

The aforementioned campuses use on-site generation while connected to the local utility grid. They depend on the grid energy in case of interruptions in energy supply or shortage in energy supply by the on-site DER. The results shown here are for on-site DER primary generation while connected to the grid for back-up electric energy. Table 22 shows the summary of energy technology allocations for the four universities. The table also shows the average weather temperatures for the respective regions in 2012 to provide insight on regional climatic conditions.

	UT	UI	SB	SF
Natural gas turbine electricity	-	-	-	19%
Natural gas turbine CHP	-	-	34%	-
Natural gas turbine CCHP	-	61%	-	-
Natural gas microturbine electricity	11%	-	-	-
Solid oxide fuel cells electricity	38%	13%	23%	51%
Wind turbine- onshore electricity	1%	1%	0.3%	-
Solar thermal collector water heater	1%	-	1%	1%
Solar thermal collector with adsorption chille	4%	-	-	-
Central receiver solar thermal electricity	-	-	-	0.03%
Biomass fired boiler	-	2%	-	-
Gas water heater	1%	-	-	4%
Geothermal ground loop heat pump	39%	20%	37%	22%
Geothermal pump with desuperheater	5%	3%	5%	3%
Average summer high (°F)	97	87	84	80
Average winter low (°F)	41	14	27	38

Table 22. Model Framework Summary Results

The model accounts for the local grid electricity and fuel prices. The selection of energy technologies is based on the campus energy demands, minimum dispatachabilities of the energy demands, and regional climatic conditions. The results of the case studies reveal several appropriate energy technologies that are essential for future energy planning. The optimum energy technology allocation must be encouraged when the campuses plan to change their on-site energy infrastructure. The regional policy makers and developers are encouraged to promote these technologies that obtained pareto-optimal solutions, offering the optimum combination of levelized costs and environment emissions.

In general, natural gas turbines are selected for the majority of energy generation because of their low cost and moderate emissions. CHP technologies are not selected for warmer climates as heating requirements are low. In complement to natural gas turbines, fuel cells are favored for electric needs in any climate as they are most efficient for electricity generation and have low emissions. These results support the findings in a 2013 Energy Information Administration's distributed generation analysis report [190].

Geothermal heat pumps are preferred for base load heating and cooling in all climates as they are renewable as well as dispatchable. But in extremely hot and cold climates, additional secondary energy technologies (e.g. boilers, cogeneration heat, etc.) must be used in conjunction with geothermal heat pumps to satisfy the excessive heating and cooling demands. Wind turbine energy is favored in all climates and solar thermal energy generation is selected in warm and sunny climates.

Chapter 7

Application to Different Large Energy Users on Long Island

This chapter presents the case studies of different types of large energy users located in a same region in the US. The purpose of the case studies in this chapter is to observe the variation in the selection of energy technologies and corresponding energy capacities due to the types of energy users in the same region. We consider Long Island, New York as the region.

Long Island, New York has warm, humid summers and cold, wet winters. Long Island climate is a combination of humid subtropical and humid continental climates [191]. Long Island has a moderately sunny climate throughout the year. Due to the coastal location, Long Island weather temperatures are somewhat mild because of the Atlantic Ocean and Long Island Sound.

We study four types of large energy users – a medical center, an enclosed shopping mall, a hotel, and an office building. These are energy intense buildings, meaning that their energy consumption is high when compared to residential or other buildings. Table 23 shows the approximate annual energy use intensity (EUI) values (kWh/SF) of the selected building types on Long Island [192] in 2012.

kWh/Square Feet	Health Care	Shopping Mall	Lodging	Office
Water Pumping	1.68	1.02	0.96	0.09
Water Heating	14.52	2.31	9.42	0.6
Space Heating	27.54	7.08	6.66	9.84
Ventilation	6	2.25	0.81	1.56
Space Cooling	5.58	3.72	1.47	2.67
Refrigeration	1.2	0.6	0.69	0.87
Lighting	12.03	8.58	7.29	6.93
Electricals and Electronics	6.93	4.53	2.49	5.31
Total	75.48	30.09	29.79	27.87

Table 23. Various Major Buildings Energy End-Use Intensities[7]

EUI represents a building's energy use as a function of its space and end-uses [193]. The EUI is expressed as energy demand per square foot of building space per calendar year. It is calculated by dividing the total energy consumed by the building in one year by the total gross floor space of the building in a particular region. Some buildings are more energy intense than the others depending on their activities (e.g. medical centers). The EUI data is available from the Energy Information Administration and the Buildings Data book databases [192] [194]. We use this data and the corresponding building floor space data to estimate the energy demands for the various selected buildings on Long Island. The following sections present each of the four case studies. We calibrate the RF values and cost of solar and wind, price of fuels, and local utility grid parameters for Suffolk County, Long Island, New York and apply the framework.

[7] The units in the original dataset were presented in thousand BTUs per SF. We converted the values into kWh per SF to be consistent with the units that are used in this dissertation. 1BTU = 0.00027kWh

7.1. Medical Center

The area of the Stony Brook University Medical Center (SBMC) in Stony Brook is approximately 541,000 square feet [195]. Table 24 shows the energy demands for various SBMC end-uses in 2012. Table 25 shows the optimal DER allocation for SBMC.

	Water Pumping	Water Heating	Space Heating	Ventilation	Space Cooling	Refrigeration	Lighting	Electrical & Electronics
Approximate energy demand in kWh (D_u)	908,880	7,855,320	14,899,140	3,246,000	3,018,780	324,600	6,508,230	3,749,130

Table 24. SBMC Approximate Energy Demands

% Energy (kWh)	Water pumping	Water heating	Space heating	Ventilation	Space cooling	Refrigeration	Lighting	Electricals and Electronics	Total Energy %
Natural gas turbine CHP	-	48%	85%	100%	-	100%	100%	90%	74%
Solid oxide fuel cells electricity	100%	-	-	-	15%	-	-	10%	3%
Gas Water Heater	-	43%	-	-	-	-	-	-	8%
Geothermal ground loop heat pump	-	-	15%	-	85%	-	-	-	13%
Geothermal pump with desuperheater	-	9%	-	-	-	-	-	-	2%

Table 25. Energy Allocation Results from Model Framework for SBMC

The optimal energy allocation consists of five technologies. There is one CHP technology selected as heating demand is relatively higher than the cooling demand. The heat and electricity from natural gas CHP turbine technology can be used for heating and electric energy demands, respectively. Solid oxide fuel cell electricity can be used for water pumping and electrical equipment when needed. Geothermal pump technology in conjunction with cogeneration heat from the gas turbine can be used to satisfy the space heating needs. In warm days, geothermal pump technology can be used to satisfy the regular cooling needs and solid oxide fuel cell electricity is used to satisfy the surplus cooling needs during the peak summer days. Water heating can be fulfilled by thermal energy from the combination of natural gas CHP turbine, natural gas water heater, and geothermal desuperheater technologies.

7.2. Enclosed Shopping Mall

The area of the Smith Haven shopping mall (SHSM) in Lake Grove is approximately 1,082,000 square feet [196]. Space cooling, heating, and lighting tends to be a large portion of energy demand in enclosed shopping malls [197]. Table 26 shows the energy demands for various SHSM end-uses in 2012. Table 27 shows optimal DER allocation for SHSM.

	Water Pumping	Water Heating	Space Heating	Ventilation	Space Cooling	Refrigeration	Lighting	Electrical & Electronics
Approximate energy demand in kWh (D_U)	1,103,640	2,499,420	7,660,560	2,434,500	4,025,040	1,298,400	9,283,560	4,901,460

Table 26. SHSM Approximate Energy Demands

% Energy (kWh)	Water pumping	Water heating	Space heating	Ventilation	Space cooling	Refrigeration	Lighting	Electricals and Electronics	Total Energy %
Natural gas turbine CHP	100%	56%	61%	-	-	100%	27%	-	33%
Solid oxide fuel cells electricity	-	-	-	100%	15%	-	73%	100%	42%
Gas Water Heater	-	8%	-	-	-	-	-	-	1%
Geothermal ground loop heat pump	-	-	39%	-	85%	-	-	-	21%
Geothermal pump with desuperheater	-	36%	-	-	-	-	-	-	3%

Table 27. Energy Allocation Results from Model Framework for SHSM

The optimal energy allocation consists of five technologies. The heat and electricity from natural gas CHP turbine technology can be used for heating and electric energy demands, respectively. Solid oxide fuel cell electricity can be used for electric needs – ventilation, lighting, and electrical equipment. Geothermal pump technology in conjunction with cogeneration heat from the gas turbine can be used to satisfy the space heating needs. Geothermal pump technology can be used to satisfy the regular cooling needs and solid oxide fuel cell electricity is used to satisfy the surplus cooling needs during the peak summer days. Water heating can be fulfilled by thermal energy from natural gas CHP turbine, geothermal desuperheater, and natural gas water heater technologies.

7.3. Lodging

The area of the Long Island Marriot hotel (LIMH) in Uniondale is approximately 164,036 square feet [198]. Water heating, space heating, and lighting are major energy end-use demands in a hotel [199]. Table 28 shows the energy demands for various LIMH end-uses in 2012. Table 29 shows optimal DER allocation for LIMH.

	Water Pumping	Water Heating	Space Heating	Ventilation	Space Cooling	Refrigeration	Lighting	Electrical & Electronics
Approximate energy demand in kWh (D_u)	157,475	1,545,219	1,092,480	132,869	241,133	113,185	1,195,822	408,450

Table 28. LIMH Approximate Energy Demands

% Energy (kWh)	Water pumping	Water heating	Space heating	Ventilation	Space cooling	Refrigeration	Lighting	Electricals and Electronic	Total Energy %
Natural gas turbine CHP	100%	18%	83%	-	-	100%	24%	100%	44%
Solid oxide fuel cells electricity	-	-	-	100%	15%	-	76%	-	21%
Gas Water Heater	-	79%	-	-	-	-	-	-	25%
Geothermal ground loop heat pump	-	-	17%	-	85%	-	-	-	9%
Geothermal pump with desuperheater	-	4%	-	-	-	-	-	-	1%

Table 29. Energy Allocation Results from Model Framework for LIMH

The optimal energy allocation consists of five technologies. Natural gas microturbine CHP technology can provide electricity and heat energy for heating and electric energy demands, respectively. Solid oxide fuel cell electricity can be used for ventilation and lighting. Geothermal pump technology in conjunction with cogeneration heat from the gas microturbine can be used to satisfy the space heating needs. Geothermal pump technology can be used to satisfy the regular cooling needs and solid oxide fuel cell electricity is used to satisfy the surplus cooling needs during the peak summer days. The high water heating demand can be fulfilled by a combination of heat from natural gas microturbine CHP, geothermal desuperheater, and natural gas water heater technologies.

7.4. Major Office Building

The area of the Canon One Park office building (CAOP) in Melville is approximately 700,000 square feet [200]. Space heating, ventilation, and space cooling are major energy end-use demands in office buildings [201]. Table 30 shows the energy demands for various CAOP end-uses in 2012. Table 31 shows optimal DER allocation for CAOP.

	Water Pumping	Water Heating	Space Heating	Ventilation	Space Cooling	Refrigeration	Lighting	Electrical & Electronics
Approximate energy demand in kWh (D_U)	63,000	420,000	6,888,000	1,092,000	1,869,000	609,000	4,851,000	3,717,000

Table 30. CAOP Approximate Energy Demands

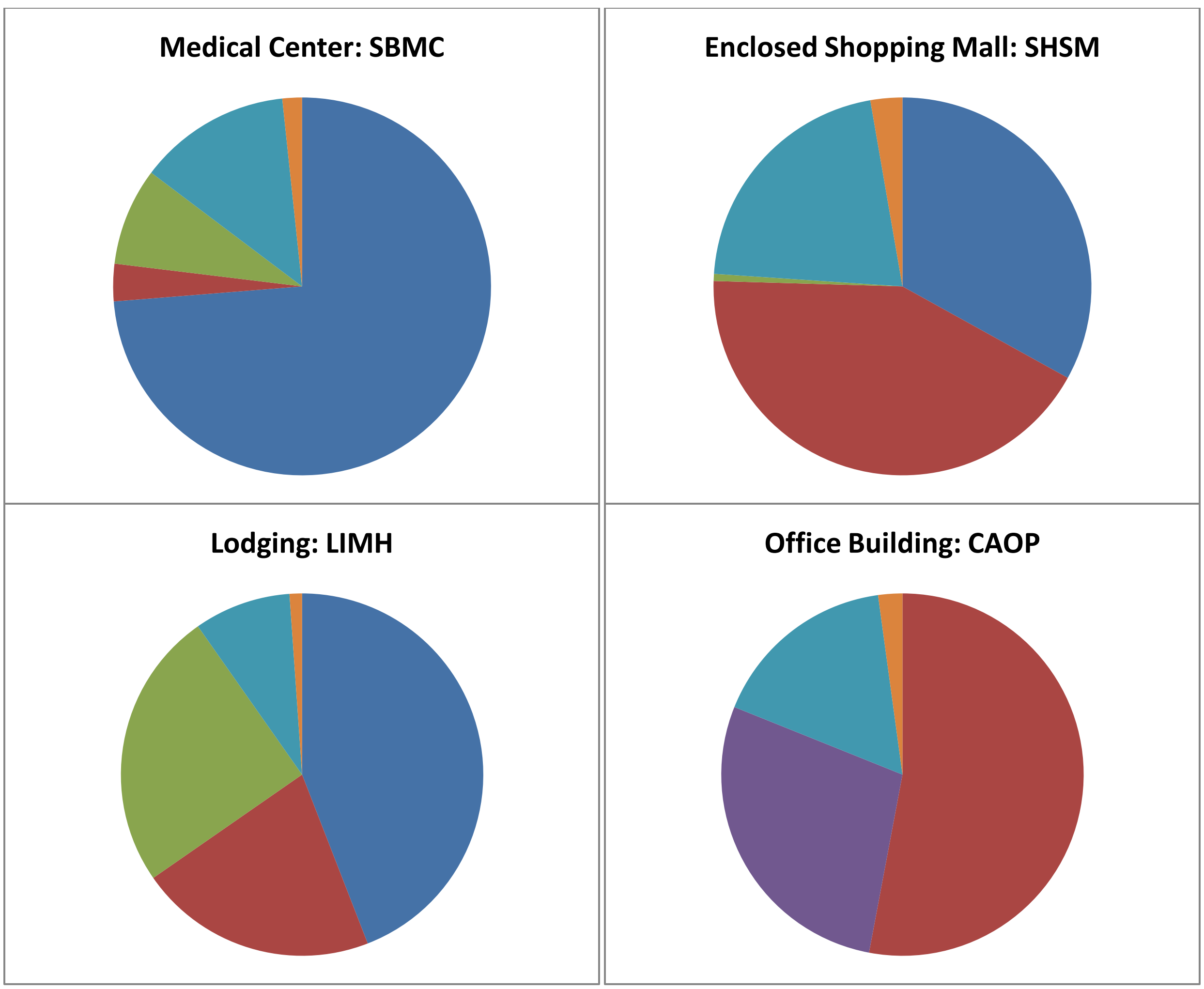
% Energy (kWh)	Water pumping	Water heating	Space heating	Ventilation	Space cooling	Refrigeration	Lighting	Electricals and Electronics	Total Energy %
Solid oxide fuel cells electricity	100%	-	-	100%	-	100%	100%	100%	53%
Gas Furnace	-	-	80%	-	-	-	-	-	28%
Geothermal ground loop heat pump	-	-	20%	-	100%	-	-	-	17%
Geothermal pump with desuperheater	-	100%	-	-	-	-	-	-	2%

Table 31. Energy Allocation Results from Model Framework for CAOP

The optimal energy allocation consists of four energy technologies. Due to both the type of building and the weather conditions, the space heating demand is high but water heating demand is low when compared to the total energy use, thus, no CHP energy technologies are selected for optimal allocation. The gas furnace technology that is highly efficient for generating thermal energy is allocated for space heating. Solid oxide fuel cell electricity is selected for all electric needs due to its high electric efficiency. Geothermal pump technology in conjunction with gas furnace technology can be used to satisfy the spacing heating needs. Space cooling demand is relatively less than the space heating demand, thus, geothermal pump technology alone can fulfill the space cooling demand. Water heating demand in office buildings is minimal and thermal energy from geothermal desuperheater is sufficient.

7.5. Summary

In the previous chapter, technology allocation was presented for the same type of user in different regions. When compared to the previous chapter, the technology selection remains the same across the different types in a same region. The selection of the energy technologies is the same for the medical center, enclosed shopping mall, and hotel. Figure 7 shows the summary of energy technology allocations to meet the total energy demand for the four different users.



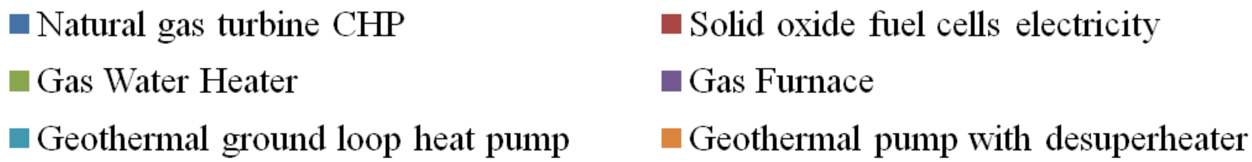


Table 7. Summary of Energy Allocation Results

In general, natural gas turbines with cogeneration are suitable for Long Island large energy users for energy generation because of their low cost and moderate emissions. Not surprisingly, natural gas turbine technology is common for small scale or large scale energy generation on Long Island. In complement to natural gas turbines, fuel cells are favored for electric needs as they are most efficient for electricity generation and have low emissions. Geothermal heat pumps are preferred for base load heating and cooling in all climates. However in the case of large heating and cooling demands, additional secondary energy technologies such as gas furnaces and boilers are selected to be used in conjunction with geothermal heat pumps in order to satisfy the excessive heating and cooling demands. Wind turbine energy and solar thermal energy generation were not selected for primary generation due to assumed minimum dispatchability of 100% for the user types and lack of land space available for the considered buildings.

The model accounts for the local grid electricity and fuel prices on Long Island, New York. The selection of energy technologies is based on the different type of users' energy demands and regional climatic conditions. The results of the case studies reveal several appropriate energy technologies that are essential for future energy planning. The optimum energy technology allocation must be encouraged when the users plan to change their on-site energy infrastructure by opting to DER. The regional policy makers and developers are encouraged to promote these technologies that obtained pareto-optimal solutions, offering the optimum combination of levelized costs and environment emissions.

Chapter 8

Implications for Public Policy

8.1. Policy Significance of the Proposed Framework

Technology philosophers claim that technologies tend to break down in size as time lapses [202] [203]. Technologies tend to atomize due to technological-push innovations by the inventors or demand-pull by the market [204] [205]. Main-frame computers were succeeded by personal computers. Similarly, landline and public telephones were taken over by cell phones on the macro-level, and traditional cell phones are transformed into smart phones at the micro-level [206].

In the US, the use of public transit systems was dominated by personal automobiles as the cost of automobiles decreased and reliability increased. As automobiles became affordable, the adoption of personal automobiles increased at a rapid pace. When Ford's *Model T* emerged in the automobile market in 1909, it attracted many middle-class Americans as it was affordable and convenient to operate [207]. These key attributes propelled the public's choice of transportation towards owning and operating personal automobiles rather than depending on public transit, though it involved a relatively high turnkey cost.

In a similar way, as DER are becoming cheaper and easier to operate, they are capturing the attention of the general public. Initially, DER were mainly used by critical energy users such as military bases, space agencies, national laboratories, etc. [1]. DER systems are disruptive innovation [3] and have a widespread potential. As small-scale energy technologies are improving and becoming more accessible, large energy users such as universities, medical centers, industries, businesses, etc. are transiting towards DER [208]. In addition, as small-scale energy technologies become cheaper, efficient, and reliable, DER adoption increases [209]. More importantly, with events such as *Superstorm Sandy* in 2012, DER adoption increases more swiftly [210].

Several decades after the inception of the first affordable automobile, the EPA highlighted the significance of energy-inefficient automobiles. The US Congress enacted the *Gas Guzzler Tax* provision in the Energy Tax Act of 1978 to discourage the production and purchase of energy inefficient automobiles [211]. In the same fashion, though DER has several advantages as discussed in chapter 1, when DER systems are not systematically regulated, they can include more natural gas or diesel generators and can potentially shift the production of conventional pollutants from central power plants to more populated areas. This complicates the problem of controlling pollution from numerous DER locations. Environmental mitigation plans such as carbon capture or sequestration will become impossible as well.

Thus, it is critical to understand the significance of optimal DER systems and establish a strategic technology-policy framework to design appropriate DER-related energy policies. This act is necessary to control the societal and environmental harms that might arise due to energy-inefficient DER systems caused by inappropriate selection of DER technologies. This research aims to assist in the preparation of necessary energy policies regarding the use of DER. This framework will help the federal, state, and local governments in regulating DER technologies for the welfare of the society and the DER users in setting their own in-house energy policies for energy management sustainability. For example, the framework provides direction to the DER developers whether it is appropriate to partially or fully depend on the local electric grid, integrate storage technologies, or have an optimum set of on-site energy generating technologies. The framework captures the local resources factor through cost and capacity constraints. For example, in the case of the University of Iowa in chapter 6, the user site was close to abundant biomass resources, thus lowering the cost of biomass due to surplus supply and negligible transportation costs. As a result, the framework selected biomass as one of the suitable energy resources available to satisfy the campus energy demand.

The strength of this research lies in the simultaneous consideration of all the available energy technologies – grid supply, storage, conventional, advanced, cogeneration, trigeneration, and renewable, and simultaneous consideration of cost, reliability, and emission factors. As DER scales up in developed nations, this research offers several implications towards local, state, or national level energy policies for the DER sector.

Firstly, this research can be used as a basis of a decision support system by the DER developers for planning and designing on-site DER infrastructure. Secondly, the proposed framework can be a useful tool for any large energy user that has the resources and desire to create its own local energy infrastructure and develop in-house energy policies. Thirdly, the proposed framework is capable of pointing to ways in which regulatory policies can encourage large energy users to adopt certain energy technologies. Part of the benefits of selective adoption of DER is the creation of relationships between DER users and regional grid level energy suppliers for long term energy planning. Such long term energy planning is beneficial in terms of coordinating energy generation and avoiding long distance transmission losses that would otherwise result in energy waste.

Finally, to convert the local optimum behavior to a global optimum behavior, extrinsic motivation must be created through subsidies for the welfare of society [212]. Based on the users' energy requirements and their regional resources, this research suggests potential target incentives and taxation policy design for implementing certain DER technologies. For example, when an incentive is provided and the cost is reduced for a technology, it reaches the efficient frontier in the first stage of the framework and becomes optimal. In this way, when users decide to adopt DER, it benefits them and their region in terms of energy sustainability and driving demand for certain technologies such as renewable technologies [213].

Moreover, in developing nations, this research can be used for developing DER systems in the regions which do not have access to an electric grid. The framework suggests suitable technologies that should be considered for particular scenarios. The proposed framework can be used in such situations to plan DER for small towns or villages based on the local resources available, geographic conditions, and the anticipated energy demand.

8.2. Policy Recommendations

There are some specific policy remarks that can be drawn towards the DER technologies based on the sensitivity analysis (chapter 5) and several case studies (chapter 6 and 7). The sensitivity analysis evaluated the sensitivity of the technology selection to the different values of the renewable percent penetration. The case studies evaluated the framework solutions to different values of the parameters of the model's objectives such as costs, energy demands, space available, local electric grid factors, etc using real scenarios. Though the results depend on particular scenario inputs, the results in general of the simulated scenarios provide some interesting insights on the DER technologies. Table 32 highlights the selective technologies from each simulated scenario. As the simulated analyses capture diverse DER applications and regions, the results provide insights for policy implications in the DER context.

	Typical Commercial Building	Sensitivity Analysis	University of Texas	University of Iowa	Stony Brook University	Stanford University	Stony Brook Medical Center	Smith Haven Shopping Mall	Canon One Office building	Long Island Marriot
Grid electricity										
Grid electricity with battery storage										
Grid electricity with pumped water storage										
Grid electricity with compressed air storage										
Grid electricity with hydrogen storage										
Diesel engine electricity										
Diesel engine CHP										
Diesel engine CCHP										
Biodiesel B-100 engine electricity		X								
Biodiesel B-100 engine CHP		X								
Biodiesel B-100 engine CCHP										
Natural gas engine electricity										
Natural gas engine CHP										
Natural gas engine CCHP										
Natural gas turbine electricity										
Natural gas turbine CHP	X	X			X	X	X	X		X
Natural gas turbine CCHP				X						
Natural gas microturbine electricity			X							
Natural gas microturbine CHP										
Natural gas microturbine CCHP										
Biomass-direct electricity										
Biomass-direct CHP										
Biomass-direct CCHP										
Polymer electrolyte membrane fuel cells electricity										
Polymer electrolyte membrane fuel cells CHP										
Phosphoric acid fuel cells electricity										
Phosphoric acid fuel cells CHP										
Molten carbonated fuel cells electricity										
Molten carbonated fuel cells CHP										
Solid oxide fuel cells electricity	X	X	X	X	X	X	X	X	X	X
Solid oxide fuel cells CHP										
Wind turbine- onshore electricity	X	X	X	X	X					
Solar photovoltaic-thin film electricity										
Solar photovoltaic- crystalline electricity										
Parabolic trough solar thermal electricity										
Central receiver solar thermal electricity						X				
Solar thermal collector water heater	X	X	X		X	X				
Solar thermal collector furnace										
Solar thermal collector with adsorption chiller	X	X	X							
Fuel oil (no.2) water heater										
Natural gas water heater			X			X	X	X		X
Oil-fired furnace / boiler										
Natural gas-fired furnace / boiler									X	
Biomass fired boiler				X						
Geothermal heat pump	X	X	X	X	X	X	X	X	X	X
Geothermal heat pump with desuperheater	X	X	X	X	X	X	X	X	X	X

Table 32. Selective Technologies

Grid and Storage Technologies

The grid electricity in all the scenarios is generated using natural gas (coal in the case of Iowa). Importantly, central power plants do not incorporate cogeneration or trigeneration setups, lowering their effective efficiency. However, grid electricity is optimum when the electricity is generated from a hydropower plant, nuclear power plant, or any other large scale renewable energy source. *Thus, grid electricity should be encouraged if the energy is generated from large scale renewable (e.g. hydro) or nuclear sources.*

Storage technologies are developing and are not cost-effective at the current moment [214]. Additionally, the storage technologies require a significant amount of space due to their limited power density. The energy storage technologies must therefore accomplish drastic cost reductions and technological improvements in terms of energy storage efficiency [215]. *Thus, research and development of storage technologies is necessary in order to make them competitive amongst the other energy technologies.* However, ultimately the storage technologies' operating economics and environmental advantages depend on the local electric grid tariff and fuel source. For example, the storage technologies will be crucial if the local power source is hydroelectric or any other renewable source [216].

Diesel Fuel Technologies

Diesel fuel is a conventional fossil fuel and diesel energy technologies are mature [3] [217]. The framework does not suggest the use of diesel technologies in any of the scenarios due to their high environmental impact and cost of diesel fuel (including transportation and storage). Compared to natural gas, diesel fuel has higher costs and emissions. In addition, diesel fuel (and also bio diesel) is more necessary for the transportation sector than for local energy generation

[218]. *Thus, diesel fuel technologies must be discouraged as primary local energy generation; standby generation for temporary back-up in case of emergencies is acceptable. Similarly, fuel oil use for heating needs must be discouraged due to their high emissions and cost.*

Natural Gas Technologies

Currently, natural gas is highly cost competitive due to its exploration through shale rock fracking [219]. As a result, the framework widely selected natural gas as a suitable energy technology, albeit through cogeneration or trigeneration due to enhanced efficiencies. Though natural gas energy generation is mature and is economically sound [217], it is a fossil fuel and involves some environmental impact (though lower than coal or diesel sources). Therefore, the choice of technologies through which the natural gas is used is critical. For example, when natural gas is combusted in a turbine, it generates heat in addition to electricity. The net efficiency of the process increases when the heat is utilized via cogeneration [117]. *Thus, natural gas must be used wisely, and its use be encouraged in conjunction with a cogeneration or trigeneration setup to maximize its usage efficiency (thereby lowering the environmental impact of natural gas consumption).*

Fuel cells use natural gas for energy production and are highly efficient as no moving parts are involved [220]. As a result, the model widely selects natural gas as an appropriate energy technology choice through fuel cell technology in all the scenarios. Although the levelized costs of fuel cells are somewhat comparable to other technologies, fuel cell setup requires high turnkey costs [221]. As fuels cells are currently expensive, they are selected only for critical electric needs, not for heating through cogeneration. Thermal energy for heating can be produced efficiently and at a low cost by using natural gas boilers or heaters, whereas capturing and using the heat from fuel cells through cogeneration is not economical due to the high cost [117]. Fuel cells offer many benefits such as high reliability, negligible noise, compact size, and most importantly their very efficient use of natural gas (or biogas) to provide electric energy [222]. They can be a potential direction to the future energy generation and can help us taper off our dependence on natural gas. Fuel cell research and development programs are essential for reducing capital costs by enabling mass production [221] [223]. *Thus, fuel cell research should be highly encouraged to lower fuel cell costs and increase their commercial appeal.*

Natural gas boilers and heaters are highly efficient (~95%) when compared to electric heating. The framework suggests natural gas boilers or heaters be used as a secondary energy source to fulfill the additional heating demand during the peak wintertime months. *Thus, natural gas is suitable for secondary heating needs when heating needs cannot be fulfilled by primary energy sources alone.* The primary energy sources include cogeneration or trigeneration heat and geothermal heat pumps.

Biofuel Technologies

Biofuels (biodiesel and biomass) are considered renewable and produce energy non-intermittently [9]. As a result, biodiesel technologies gain interest when the renewable percent increases and dispatchability of energy demand remains high, or when the biodiesel is readily locally available. Though biofuels are considered renewable fuels by definition, their emissions are relatively high when compared to natural gas [224]. The cost of biodiesel fuel and maintenance of biodiesel combustion engines makes the technology not competitive in general [225]. However, biofuels can become competitive when they are locally available due to local production or as byproducts from local food or wood-based industries [226]. For example, the model selects biomass as an appropriate heating technology at the University of Iowa, as biomass is available near Iowa City (lowering the cost) due to various food product industries that produce biomass as a waste byproduct. *Thus, biofuels must be encouraged only when they are locally available for cost-wise competitive advantages. As biofuel emissions are comparable to traditional fossil fuels, biofuel usage must be encouraged in conjunction with emissions mitigating technologies such as scrubbers, catalysts, sequesters, etc. to ease the environmental impact* [227]. Biomass fuels tend to contain impurities that may pose complications when used in turbines or engines for electric energy generation rather than boilers or heaters (e.g. biomass fired boiler) for thermal energy generation [228] . This negatively impacts economic and technical aspects of energy generation [229]. *Thus, the use of biofuels must be carefully accessed while selecting for electric needs versus for heating needs.*

Wind Technologies

The framework suggests the use of wind turbine electricity for reschedulable energy demands. Wind turbines, when compared to solar, have the benefit of economies of scale and relatively less intermittent energy production (energy during nights is possible). However, a large space with spacious surroundings is required for wind turbines. *Thus, wind turbines must be strongly encouraged when there is enough space and unobstructed wind flow.*

Solar Technologies

Based on the framework results, the solar photovoltaic's (PV) cost must be further reduced to make them competitive with wind turbines for primary energy production on a large scale (e.g. for a university) [230]. This remark does not include incremental solar PV application to residential rooftops. Currently, solar PV technologies are used as an accessory source in universities for applications (e.g. lighting the bus stops, parking pay stations, and etc.), but not as a significant source of energy (e.g. Cornell, Stony Brook, etc.). Based on the scenario results, wind turbines seem to be more suitable than solar panels as a significant energy source [231]. *Thus, solar PV must be encouraged for incremental energy generation for the residential sector more than for the large energy users due to their limited economies of scale and limited power supply.*

On the other hand, solar thermal electricity technologies convert solar energy to steam that can be used to produce energy through steam turbines at any time [232]. As a result, solar thermal when compared to solar PV offers economies of scale and increased availability as they can provide energy on a large scale and during the night [233]. Solar thermal electricity is chosen in one scenario where there is abundant sunshine and space – Stanford University in California. *Thus, solar thermal must be considered an option for significant energy generation when there is space available.*

Solar energy is widely suggested for water heating. Solar water heating technology is cost efficient and environmentally friendly when compared to conventional water heating technologies [234]. *Thus, solar energy must be encouraged for water heating due to its cost and environmental advantages, but might be limited in extremely cold regions due to requiring protection of the pipes and the tanks from freezing.*

Solar energy is suggested as a secondary source for space cooling during peak summer days. Solar energy is abundant in summer, especially during peak summer days, and can be used to make chilled water for space cooling purposes. However, solar cooling is in the development stage and is not yet commercially successful due to large space requirements and high maintenance [235]. *There is a future research need in the solar cooling technologies area.*

Geothermal Pump Technologies

Geothermal heat pumps are a sustainable energy technology as they use thermal energy from the earth's surface [236]. Therefore, they can be used as a primary source to meet heating needs in winter and cooling needs in summer. Standby gas heaters or other secondary technologies can be used for excess peak demands. Geothermal heat pump technology is highly suggested in all the scenarios due to its constant availability, high reliability, negligible operating cost, and emissions [237]. Currently, geothermal heat pumps are developing and involve high capital cost which is a major issue, but the levelized cost throughout the life of the system is less than the conventional heating and cooling systems, with environmental advantages. *Thus, geothermal heat pumps must be highly encouraged for primary heating and cooling needs and more research is needed for further decrease in capital costs.*

The aforementioned recommendations are for primary energy generation for large energy users who wish to use DER. Table 33 summarizes the policy recommendations based on the simulated analyses.

Energy Resource	Policy Implications
Grid and Storage	• Grid electricity should be highly encouraged if the energy is generated from large-scale renewable (e.g. hydro) or nuclear sources. • Research and development is necessary for the storage technologies in order to make them competitive amongst the other energy technologies.
Diesel and Fuel Oil	• Must be discouraged for primary local energy generation. • Standby generation for temporary back-up in case of emergencies can be permitted. • Fuel oil heating must be discouraged due to their high emissions and cost.
Natural Gas	• Gas turbines must be wisely encouraged in conjunction with a cogeneration or trigeneration setup to maximize usage efficiency and lower environmental impact of natural gas consumption. • Natural gas based fuel cells must be encouraged. • Fuel cell research should be highly encouraged to lower their cost and make them commercially appealing. • Natural gas is suitable for secondary heating needs when heating needs cannot be fulfilled by the primary energy sources alone.
Biofuels	• Must be encouraged only when they are locally available for cost-wise competitive advantages. • Must be encouraged in conjunction with emissions mitigating technologies such as scrubbers, catalysts, sequesters, etc. to ease the environmental impact of biofuel consumption. • Must be carefully accessed while selecting for electric needs versus heating needs.
Wind	• Must be strongly encouraged when there is enough space and unobstructed wind flow.
Solar	• Solar PV must be encouraged for incremental energy generation for the residential sector more than for large energy users due to limited economies of scale and limited power supply. • Solar thermal electricity must be considered to be a significant source of energy when there is space available. • Solar energy must be encouraged for water heating due to cost and environmental advantages, but might be limited in extremely cold regions due to required protection of the pipes and the tanks from freezing. • Solar cooling needs additional research and development.
Geothermal	• Must be highly encouraged for primary heating and cooling needs. • More research is needed to further decrease capital costs.

Table 33. Summary of Policy Recommendations

Chapter 9

Conclusion

This dissertation presents a novel two-stage strategic DER technology-policy framework for determining the optimal energy technology allocation. The methodology simultaneously considers economic, technical, and environmental objectives. The first stage utilizes a data envelopment analysis model for each end-use to evaluate the performance of each technology based on the three objectives. The second stage incorporates factor efficiencies determined by the DEA models, capacity limitations, dispatchability, and renewable penetration for each technology, and demand for each end-use into a bottleneck multi-criteria decision model which provides the optimal energy resource allocation. This framework accommodates both the needs of users and regulators.

The proposed framework avoids the need to subjectively specify weights and targets associated with the individual objectives. Moving forward, the model framework will enable DER developers, users, and policy makers to better understand the competitiveness of individual DER energy technologies for different end-uses. We anticipate these stakeholders will utilize the framework to determine optimal energy technology allocation and to develop regulatory policy driven by the model outputs.

Chapter 1 introduces the nature of DER, potential concerns, and the research question and its significance. Chapter 2 presents the background literature, gaps in the literature, and the novelty of this dissertation. Chapter 3 describes the systems theory of the DER, and sets up the metrics. Chapter 4 sets up the research design and explains the mathematical model in detail. In chapter 5, the functionality of the framework was demonstrated using a typical commercial building scenario in the New York region. We discussed the results and performed sensitivity analysis by varying the renewable percentage to observe the shift in energy technologies and change in costs and emissions.

We performed eight case studies to demonstrate the utility and robustness of the framework. In chapter 6, we performed four case studies where we treat the user type as a constant and collected data from universities from four different regions in the US. The purpose of the chapter is to understand the role of variation in the regions towards the selection of DER. In chapter 7, we performed four case studies where we treat the region of the users as constant and collected data for four different large energy users in the same region (Long Island). The purpose of the chapter is to understand how the energy technology selection varies for each user type. Chapter 8 discusses the policy implications of this dissertation.

9.1. Limitations and Future Work

This research does not intend to assist with tactical everyday energy usage; it is for assisting decision making at the planning stage of DER systems. However, it can be further developed into a dynamic tactical tool. Considering the static life cycle model used in this study and the long life span of a typical building, dynamic modeling can provide more insight. The current projections about variations in a building are extremely complex and cumbersome, and are beyond the scope of this dissertation. Further research is required to accommodate building characteristics into this framework [177].

Similarly, the proposed framework is a deterministic model and is not set to consider any uncertainty in data. Examples of uncertainty in data include fluctuation in energy demand, change in climatic conditions, change in costs, etc. The framework requires cumbersome data forecasting and collection. The results of the model are sensitive to the input data. Thus, the precision of the data is critical. The proposed framework can be advanced to a stochastic model by incorporating simulation. This will allow the analyst to use a range of data points, for example: range of summer temperatures, range of natural gas prices, etc. However, this will add complexity to the existing framework and make it more data intense. This might limit the model's functionality for high-level energy policy planning applications.

In addition, the framework does not intend to perform life-cycle analysis of the energy technologies. Perhaps the framework feeds on the results of such prior analysis. The framework does not provide insights on the optimal power flow schemes between an on-site DER system and the local electric grid. The framework assumes the possibility of DER setup in conjunction with the local electric grid or in an islanded mode. The framework does not regard any challenges that might complicate the connection of on-site DER to the local electric grid. Such challenges may include local utility policies, the age of the grid, voltage surges, and peak and off-peak demand patterns.

In US transportation history, as more people acquired personal automobiles, public transit demand declined and public transit faced economic challenges. The public transit systems currently operate on heavy public subsidization [238]. Likewise, as DER evolves, the economics of the aging regional electric grids may be strained and might require public subsidies to function, and the users who depend on the regional grids may face increased costs. However, dealing with this issue is out of the scope of this dissertation. Though the framework considers local grid reliability as a criterion, local grid reliability issues are not addressed in this research.

All these issues together present a direction for future research.

Bibliography

[1] Marnay C, Nordman B, Lai J. Future Roles of Mill-, Micro-, and Nano- Grids. In: Division EET, editor. CIGRE International Symposium: The electric power system of the future: Ernest Orlando Lawrence Berkeley National Labaratory; 2011.

[2] Marnay C. Challenges of Supply: An Evolving Energy Paradigm. Power and Energy Magazine, IEEE2013. p. 100-4.

[3] Borbely A-M, Kreider JF. Distributed Generation: The Power Paradigm for the New Millennium. CRC Press; 2010.

[4] Federal Energy Technology Center F. Distributed Generation. In: DOE US, editor.: Distributed Power Coalition of America (DPCA); 1999.

[5] Cardell J, Tabors R. Operations and Control in a Competitive Market: Distributed Generation in a Restructured Industry Energy. 1998:111-35.

[6] Sharma D, Bartels R. Distributed electricity generation in competitive energy markets. Energy. 1998:17-40.

[7] International Energy Agency I. Distributed Generation in Liberalised Electricity Markets. Paris, France: OCED/IEA Publication Service; 2002.

[8] Firestone R, Marnay C. Energy Manager Design for Microgrids. Berkeley, California: Lawrence Berkeley National Laboratory; 2005.

[9] Pepermans G, Driesen J, Haeseldonckx D, Belmans R, D'haeseleer W. Distributed generation: definition, benefits and issues. Energ Policy. 2005;33:787-98.

[10] Lund H, Munster E. Modelling of energy systems with a high percentage of CHP and wind power. Renew Energ. 2003;28:2179-93.

[11] Guttromson RT. Modeling Distributed Energy Resource Dynamics on the Transmission System. IEEE Transactions on Power Systems. 2002;17:1148-53.

[12] Carpinelli G, Celli G, Mocci S, Pilo F, Russo A. Optimisation of embedded generation sizing and siting by using a double trade-off method. IEEE Proceedings - Generation, Transmission and Distribution2005. p. 503-13.

[13] Joskow PL. Transmission policy in the United States. Utilities Policy. 2005;13:95-115.

[14] Moradi MH, Abedini M. A combination of genetic algorithm and particle swarm optimization for optimal DG location and sizing in distribution systems. International Journal of Electrical Power & Energy Systems. 2012;34:66-74.

[15] Popovic DH, Greatbanks JA, Begovic M, Pregelj A. Placement of distributed generators and reclosers for distribution network security and reliability. International Journal of Electrical Power & Energy Systems. 2005;27:398-408.

[16] Alanne K, Saari A. Distributed Energy Generation and Sustainable Development. Renewable and Sustainable Energy Reviews. 2006;10:539-58.

[17] Morris G, Abbey C, Joos G, Marnay C. A Framework for the Evaluation of the Cost and Benefits of Microgrids. CIGRÉ International Symposium Bologna, Italy 2011.

[18] Coaffee J. Risk, resilience, and environmentally sustainable cities. Energ Policy. 2008;36:4633-8.

[19] Jiayi H, Chuanwen J, Rong X. A review on distributed energy resources and MicroGrid. Renewable and Sustainable Energy Reviews. 2008;12:2472-83.

[20] Akorede MF, Hizam H, Pouresmaeli E. Distributed energy resources and benefits to the environment. Renewable and Sustainable Energy Reviews. 2010;14:724-34.

[21] Mancarella P, Chicco G. Global and local emission impact assessment of distributed cogeneration systems with partial-load models. Appl Energ. 2009;86:2096-106.

[22] Strachan N, Farrell A. Emission from distributed vs. centralized generation: the importance of system performance. Energ Policy. 2006;34:2677-89.

[23] Chandel A, Chauhan DS, Singh D. Distributed Generation Planning in Deregulated Power Market - A Bibliographical Surver. International Journal of Energy Technology and Policy. 2012;8:267-85.

[24] U.S. Energy Information Administration E. Annual Energy Outlook 2013. In: Energy Do, editor. Washington, DC.: Office of Integrated and International Energy Analysis; 2013.

[25] Fanchi JR, Fanchi CJ. Energy in the 21st Century. 2nd ed: World Scientific Publishing Company; 2010.

[26] Mowery DC. Economic-Theory and Government Technology Policy. Policy Sci. 1983;16:27-43.

[27] Rogers EM. Diffusion of Innovations. 5th ed. New York, NY: Free Press; 2003.

[28] Ackermann T, Andersson G, Soder L. Distributed Generation: A Definition. Electric Power Systems Research. 2001;57:195-204.

[29] Pudjianto D, Ramsay C, Strbac G. Virtual power plant and system integration of distributed energy resources. Renewable Power Generation. 2007;1:10-6.

[30] Katiraei F, Iravani MR. Power management strategies for a microgrid with multiple distributed generation units. IEEE Transactions on Power Systems. 2006;21:1821-31.

[31] Asmus P. Microgrids, virtual power plants and our distributed energy future. The Electricity Journal. 2010;23:72-82.

[32] Hatziargyriou N, Asano H, Iravani R, Marnay C. Microgrids. Ieee Power Energy M. 2007;5:78-94.

[33] Pohekar SD, Ramachandran M. Application of multi-criteria decision making to sustainable energy planning - A review. Renew Sust Energ Rev. 2004;8:365-81.

[34] Figueira J, Greco S, Ehrgott M. Multiple criteria decision analysis: state of the art surveys. Vertag: Springer; 2005.

[35] Loken E. Use of multicriteria decision analysis methods for energy planning problems. Renew Sust Energ Rev. 2007;11:1584-95.

[36] Alarcon-Rodriguez A, Ault G, Galloway S. Multi-objective planning of distributed energy resources: A review of the state-of-the-art. Renewable and Sustainable Energy Reviews. 2010;14:1353-66.

[37] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energ. 2010;87:1059-82.

[38] Fadaee M, Radzi MAM. Multi-objective optimization of a stand-alone hybrid renewable energy system by using evolutionary algorithms: A review. Renew Sust Energ Rev. 2012;16:3364-9.

[39] Celli G, Ghiani E, Mocci S, Pilo F. A multi-objective formulation for the optimal sizing and siting of embedded generation in distribution networks Power Tech Conference. Bologna, Italy: Power Tech Conference Proceedings; 2003.

[40] Harrison GP, Wallace AR. Optimal power flow evaluation of distribution network capacity for the connection of distributed generation. Iee P-Gener Transm D. 2005;152:115-22.

[41] Harrison GP, Piccolo A, Siano P, Wallace AR. Hybrid GA and OPF evaluation of network capacity for distributed generation connections. Electric Power Systems Research. 2008;78:392-8.

[42] Keane A, O'Malley M. Optimal allocation of embedded generation on distribution networks. IEEE Transactions on Power Systems. 2005;20:1640-6.

[43] Ooka R, Komamura K. Optimal design method for building energy systems using genetic algorithms. Build Environ. 2009;44:1538-44.

[44] Voll P, Klaffke C, Hennen M, Bardow A. Automated superstructure-based synthesis and optimization of distributed energy supply systems. Energy. 2013;50:374-88.

[45] Ashouri A, Fux SS, Benz MJ, Guzzella L. Optimal design and operation of building services using mixed-integer linear programming techniques. Energy. 2013;59:365-76.

[46] Kim JO, Nam SW, Park SK, Singh C. Dispersed generation planning using improved Hereford ranch algorithm. Electric Power Systems Research. 1998;47:47-55.

[47] Wang CS, Nehrir MH. Analytical approaches for optimal placement of distributed generation sources in power systems. IEEE Transactions on Power Systems. 2004;19:2068-76.

[48] Wang WM, Zmeureanu R, Rivard H. Applying multi-objective genetic algorithms in green building design optimization. Build Environ. 2005;40:1512-25.

[49] Soroudi A, Ehsan M, Zareipour H. A practical eco-environmental distribution network planning model including fuel cells and non-renewable distributed energy resources. Renew Energ. 2011;36:179-88.

[50] Niknam T, Azizipanah-Abarghooee R, Narimani MR. An efficient scenario-based stochastic programming framework for multi-objective optimal micro-grid operation. Appl Energ. 2012;99:455-70.

[51] Menon RP, Paolone M, Marechal F. Study of optimal design of polygeneration systems in optimal control strategies. Energy. 2013;55:134-41.

[52] Zhou Z, Liu P, Li Z, Ni WD. An engineering approach to the optimal design of distributed energy systems in China. Appl Therm Eng. 2013;53:387-96.

[53] Handschin E, Neise F, Neumann H, Schultz R. Optimal operation of dispersed generation under uncertainty using mathematical programming. International Journal of Electrical Power & Energy Systems. 2006;28:618-26.

[54] Willis HL, Scott WG. Distributed power generation. Planning and evaluation. New York: Marcel Dekker; 2000.

[55] Dugan RC, McDermott TE, Ball GJ. Planning for distributed generation. Ieee Ind Appl Mag. 2001;7:80-8.

[56] El-Khattam W, Hegazy YG, Salama MMA. An integrated distributed generation optimization model for distribution system planning. IEEE Transactions on Power Systems. 2005;20:1158-65.

[57] Celli G, Pilo F. Optimal distributed generation allocation in MV distribution networks. 22nd IEEE PES international conference on power industry computer applications PICA 2001. Sydney, Australia2001. p. 81-6.

[58] Wright A, Firth S. The nature of domestic electricity-loads and effects of time averaging on statistics and on-site generation calculations. Appl Energ. 2007;84:389-403.

[59] Kalantar M, Mousavi SM. Dynamic behavior of a stand-alone hybrid power generation system of wind turbine, microturbine, solar array and battery storage. Appl Energ. 2010;87:3051-64.

[60] Fumo N, Mago PJ, Chamra LM. Analysis of cooling, heating, and power systems based on site energy consumption. Appl Energ. 2009;86:928-32.

[61] Van Schijndel AVM. Optimal operation of a hospital power plant. Energ Buildings. 2002;34:1155-65.

[62] Cardona E, Piacentino A, Cardona F. Energy saving in airports by trigeneration. Part I: Assessing economic and technical potential. Appl Therm Eng. 2006;26:1427-36.

[63] Ziher D, Poredos A. Economics of a trigeneration system in a hospital. Appl Therm Eng. 2006;26:680-7.

[64] Arcuri P, Florio G, Firagiacomo P. A mixed integer programming model for optimal design of trigeneration in a hospital complex. Energy. 2007;32:1430-47.

[65] Casisi M, Pinamonti P, Reini M. Optimal lay-out and operation of combined heat & power (CHP) distributed generation systems. Energy. 2009;34:2175-83.

[66] Houwing M, Ajah AN, Heijnen PW, Bouwmans I, Herder PM. Uncertainties in the design and operation of distributed energy resources: the case of micro-CHP systems. Energy. 2008;33:1518-36.

[67] Lozano MA, Ramos JC, Serra LM. Cost optimization of the design of CHCP (combined heat, cooling and power) systems under legal constraints. Energy. 2010;35:794-805.

[68] Wakui T, Yokoyama R, Shimizu K. Suitable operational strategy for power interchange operation using multiple residential SOFC (solid oxide fuel cell) cogeneration systems. Energy. 2010;35:740-50.

[69] Marnay C, Chard JS, Hamachi KS, Lipman T, Moezzi MM, Ouaglal B, et al. Modeling of Customer Adoption of Distributed Energy Resources. Berkeley, California: Ernest Orlando Lawrence Berkeley National Laboratory; 2001.

[70] BerkeleyLab. DER-CAM. Lawrence Berkeley National Laboratory; 2013.

[71] Marnay C, Stadler M, Siddiqui AS, DeForest N, Bhattacharya P, Lai J. Applications of Optimal Building Energy System Selection and Operation. Environmental Energy Technologies Division: Lawrence Berkeley National Laboratory 2013.

[72] Marnay C, Stadler M, Siddiqui AS, DeForest N, Donadee J, Bhattacharya P, et al. Applications of Optimal Building Energy System Selection and Operation. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. 2013;227:82-93.

[73] Dincer I. Environmental impacts of energy. Energ Policy. 1999;27:845-54.

[74] Pehnt M. Environmental impact of distributed energy systems – the case of micro cogeneration. Environmental Science Policy. 2008;2:25-37.

[75] Allison JE, Lents J. Encouraging distributed generation of power that improves air quality: can we have our cake and eat it too? Energ Policy. 2002;30:737-52.

[76] Chicco G, Mancarella P. Assessment of the greenhouse gas emissions from cogeneration and trigeneration systems. Part I: Models and indicators. Energy. 2008;33:410-7.

[77] Mancarella P, Chicco G. Assessment of the greenhouse gas emissions from cogeneration and trigeneration systems. Part II: Analysis techniques and application cases. Energy. 2008;33:418-30.

[78] Bang G. Energy security and climate change concerns: Triggers for energy policy change in the United States? Energ Policy. 2010;38:1645-53.

[79] Canova A, Chicco G, Genon G, Mancarella P. Emission characterization and evaluation of natural gas-fueled cogeneration microturbines and internal combustion engines. Energ Convers Manage. 2008;49:2900-9.

[80] Meunier F. Co- and tri-generation contribution to climate change control. Appl Therm Eng. 2002;22:703-18.

[81] Ren HB, Zhou WS, Nakagami K, Gao WJ, Wu QO. Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects. Appl Energ. 2010;87:3642-51.

[82] Haesen E, Driesen J, Belmas R. A long-term multi-objective planning tool for distributed energy resources. Proceedings of IEEE PES power systems conference & exposition. USA2006. p. 741-7.

[83] Haesen E, Espinoza M, Pluymers B, Goethals I, Van Thong V, Driesen J. Optimal placement and sizing of distributed generator units using genetic optimization algorithms. Electrical Power Quality and Utilisation Journal. 2005;11:97-104.

[84] Celli G, Ghiani E, Mocci S, Pilo F. A multi-objective evolutionary algorithm for the sizing and siting of distributed generation. IEEE Transactions on Power System2005.

[85] Celli G, Soma GG, Gallanti M, Cicoria R. Active distribution network cost/benefit analysis with multi-objective programming. Proceedings 20th international conference on electricity distribution CIRED 2009. Prague2009.

[86] Tsay MT. Applying, the multi-objective approach for operation strategy of cogeneration systems under environmental constraints. International Journal of Electrical Power & Energy Systems. 2003;25:219-26.

[87] Aki H, Murata A, Yamamoto S, Kondoh J, Maeda T, Yamaguchi H, et al. Penetration of residential fuel cells and CO2 mitigation - case studies in Japan by multi-objective models. Int J Hydrogen Energ. 2005;30:943-52.

[88] Zangeneh A, Jadid S. Normal boundary intersection for generating pareto set in distributed generation planning. Proceedings of international power engineering conference2007. p. 1077-82.

[89] Gholap AK, Khan JA. Design and multi-objective optimization of heat exchangers for refrigerators. Appl Energ. 2007;84:1226-39.

[90] Celli G, Mocci S, Soma GG. A Multi-Objective Approach for the Optimal Distributed Generation Allocation with Environmental Constraints. Probabilistic Methods Applied to Power Systems. Rincon 2008. p. 1-8.

[91] Mavrotas G, Diakoulaki D, Florios K, Georgiou P. A mathematical programming framework for energy planning in services' sector buildings under uncertainty in load demand: The case of a hospital in Athens. Energ Policy. 2008;36:2415-29.

[92] Sayyaadi H, Amlashi EH, Amidpour M. Multi-objective optimization of a vertical ground source heat pump using evolutionary algorithm. Energ Convers Manage. 2009;50:2035-46.

[93] Gebreslassie BH, Guillen-Gosalbez G, Jimenez L, Boer D. Design of environmentally conscious absorption cooling systems via multi-objective optimization and life cycle assessment. Appl Energ. 2009;86:1712-22.

[94] Sayyaadi H. Multi-objective approach in thermoenvironomic optimization of a benchmark cogeneration system. Appl Energ. 2009;86:867-79.

[95] Kavvadias KC, Maroulis ZB. Multi-objective optimization of a trigeneration plant. Energ Policy. 2010;38:945-54.

[96] Carvalho M, Lozano MA, Serra LM. Multicriteria synthesis of trigeneration systems considering economic and environmental aspects. Appl Energ. 2012;91:245-54.

[97] Haesen E, Deconinck G, Driesen J, Belmans R. Planning of distributed energy resources: traditional optimization tools versus evolutionary algorithms. Influence of distributed and renewable generation on power system security—CRIS. Magdeburg, Germany2006. p. 190-9.

[98] Harrison GP, Piccolo A, Siano P, Wallace AR. Distributed Generation Capacity Evaluation Using Combined Genetic Algorithm and OPF. International Journal of Emerging Electric Power Systems. 2007;8.

[99] Harrison GP, Piccolo A, Siano P, Wallace AR. Exploring the trade-offs between incentives for distributed generation developers and DSO's. IEEE Transactions on Power Systems2007.

[100] Becerra-Lopez HR, Golding P. Multi-objective optimization for capacity expansion of regional power-generation systems: Case study of far west Texas. Energ Convers Manage. 2008;49:1433-45.

[101] Tang X, Tang G. Multi-objective planning for distributed generation in distribution network. Third international conference on electric utility deregulation and restructuring and power technologies, DRPT 2008. Nanjing, China2008.

[102] Saaty TL. The Analytic Hierarchy Process. New York: McGraw-Hill; 1980.

[103] Alarcon-Rodriguez A, Haesen E, Ault G, Driesen J, Belmans R. Multi-objective planning framework for stochastic and controllable distributed energy resources. Renewable Power Generation. 2009;3:227-38.

[104] Haesen E, Alarcon-Rodriguez A, Driesen J, Belmans R, Ault GW. Opportunities for active DER management in deferral of distribution system reinforcements. 2009 IEEE Power Systems Conference & Exposition. Seattle, USA2009.

[105] Abdollahi G, Meratizaman M. Multi-objective approach in thermoenvironomic optimization of a small-scale distributed CCHP system with risk analysis. Energ Buildings. 2011;43:3144-53.

[106] Rubio-Maya C, Uche-Marcuello J, Martinez-Gracia A, Bayod-Rujula AA. Design optimization of a polygeneration plant fuelled by natural gas and renewable energy sources. Appl Energ. 2011;88:449-57.

[107] Fazlollahi S, Mandel P, Becker G, Marechal F. Methods for multi-objective investment and operating optimization of complex energy systems. Energy. 2012;45:12-22.

[108] Fazlollahi S, Becker G, Marechal F. Multi-Objectives, Multi-Period Optimization of district energy systems: II-Daily thermal storage. Computers & Chemical Engineering. 2013;(in press).

[109] Pelet X, Favrat D, Leyland G. Multi-objective optimization of integrated energy systems for remote communities considering economics and CO2 emissions. International Journal of Thermal Sciences. 2005;44:1180-9.

[110] Alarcon-Rodriguez A, Ault GW, Currie RAF, McDonald JR. Planning highly distributed power systems: effective techniques and tools. International Journal of Distributed energy Resources. 2008;4.

[111] Moura PS, de Almeida AT. Multi-objective optimization of a mixed renewable system with demand-side management. Renew Sust Energ Rev. 2010;14:1461-8.

[112] Fesanghary M, Asadi S, Geem ZW. Design of low-emission and energy-efficient residential buildings using a multi-objective optimization algorithm. Build Environ. 2012;49:245-50.

[113] El-Khattam W, Salama MMA. Distributed generation technologies, definitions and benefits. Electric Power Systems Research. 2004;71:119-28.

[114] Chicco G, Mancarella P. Distributed multi-generation: A comprehensive view. Renew Sust Energ Rev. 2009;13:535-51.

[115] Mezher T, Chedid R, Zahabi W. Energy resource allocation using multi-objective goal programming: the case of Lebanon. Appl Energ. 1998;61:175-92.

[116] Ramanathan R, Ganesh LS. Energy Resource Allocation Incorporating Qualitative and Quantitative Criteria: An Integrated Model Using Goal Programming and AHP. Socio-Economic Planning Sciences. 1995;29:197-218.

[117] U.S. Environmental Protection Agency E. The Catalog of CHP Technologies. In: Agency USEP, editor.: Combined Heat and Power Partnership; 2008.

[118] Barba-Gutierrez Y, Adenso-Diaz B, Lozano S. Eco-Efficiency of Electric and Electronic Appliances: A Data Envelopment Analysis (DEA). Environ Model Assess. 2009;14:439-47.

[119] Boyce MP. Gas turbine engineering handbook. 4th ed. Amsterdam ; Boston: Elsevier/Butterworth-Heinemann; 2012.

[120] Electric G. Fluorescent Lamps Technical Bulletin TP 111R. 1978. p. 10-1.

[121] Agrawal RK, Singh SP. Energy allocations for cooking in UP households (India) - A fuzzy multi-objective analysis. Energ Convers Manage. 2001;42:2139-54.

[122] Allen SR, Hammond GP, McManus MC. Prospects for and barriers to domestic micro-generation: A United Kingdom perspective. Appl Energ. 2008;85:528-44.

[123] Mathiesen BV, Lund H. Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources. Iet Renew Power Gen. 2009;3:190-204.

[124] Cho HJ, Mago PJ, Luck R, Chamra LM. Evaluation of CCHP systems performance based on operational cost, primary energy consumption, and carbon dioxide emission by utilizing an optimal operation scheme. Appl Energ. 2009;86:2540-9.

[125] LAZARD. Levelized cost of energy analysis. 2009.

[126] Doty GN, McCree DL, Doty FD. Projections of Levelized cost benefit of Grid-Scale Energy Storage Options. Energy Sustainability 2010. Phoenix, Arizona: Proceedings of ES2010; 2010.

[127] National Renewable Energy Laboratory N. Performance and Reliability R&D. 2013.

[128] Jacobsson S, Johnson A. The diffusion of renewable energy technology: an analytical framework and key issues for research. Energ Policy. 2000;28:625-40.

[129] Skone T. Life Cycle Analysis. www.netl.doe.gov: National Energy Technology Lab; 2013.

[130] Weisser D. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. Energy. 2007;32:1543-59.

[131] Soytas U, Sari R, Ewing BT. Energy consumption, income, and carbon emissions in the United States. Ecol Econ. 2007;62:482-9.

[132] Hameed S, Dignon J. Global Emissions of Nitrogen and Sulfur-Oxides in Fossil-Fuel Combustion 1970-1986. J Air Waste Manage. 1992;42:159-63.

[133] U.S. Environmental Protection Agency E. Air Emission Sources. 2013.

[134] Shaha AK. Combustion Engineering and Fuel Technology: Optimum Utilization of Fuels. New Delhi: Oxford & IBH Publishing Company; 1974.

[135] Chedid R, Mezher T, Jarrouche C. A fuzzy programming approach to energy resource allocation. International Journal of Energy Research. 1999;23:303-17.

[136] Antipova E, Boer D, Cabeza LF, Guillen-Gosalbez G, Jimenez L. Uncovering relationships between environmental metrics in the multi-objective optimization of energy systems: A case study of a thermal solar Rankine reverse osmosis desalination plant. Energy. 2013;51:50-60.

[137] Bell ML, Hobbs BF, Elliott EM, Ellis H, Robinson Z. An evaluation of multicriteria decision-making methods in integrated assessment of climate policy. Lect Notes Econ Math. 2000;487:228-37.

[138] Zhou P, Ang BW, Poh KL. Decision analysis in energy and environmental modeling: An update. Energy. 2006;31:2604-22.

[139] Ramanathan R, Ganesh LS. A multi-objective programming approach to energy resource allocation problems. International Journal of Energy Research. 1993;17:105-19.

[140] Lewis HF. Using DEA factor efficiency scores to eliminate subjectivity in goal programming. Advances in Operations Research. 2011;2011.

[141] Energy Efficiency & Renewable Energy E. 2011 Buildings Energy Data Book. In: Energy USDo, editor.: Buildings Technologies Program; 2012.

[142] Li H, Fu L, Geng KC, Jiang Y. Energy utilization evaluation of CCHP systems. Energ Buildings. 2006;38:253-7.

[143] Mago PJ, Chamra LM, Hueffed A. A review on energy, economical, and environmental benefits of the use of CHP systems for small commercial buildings for the North American climate. International Journal of Energy Research. 2009;33:1252-65.

[144] Mago PJ, Fumo N, Chamra LM. Performance analysis of CCHP and CHP systems operating following the thermal and electric load. International Journal of Energy Research. 2009;33:852-64.

[145] U.S. Department of Energy D. Energy Savings Potential and R&D Opportunities for Commercial Refrigeration. Building Technologies Program: Energy Efficiency and Renewable Energy; 2009.

[146] Srikhirin P, Aphornratana S, Chungpaibulpatana S. A review of absorption refrigeration technologies. Renewable and Sustainable Energy Reviews. 2001;5:343-72.

[147] Lorentzen G. The Use of Natural Refrigerants - a Complete Solution to the Cfc/Hcfc Predicament. Int J Refrig. 1995;18:190-7.

[148] Charnes A, Cooper WW, Rhodes E. Measuring Efficiency of Decision-Making Units. Eur J Oper Res. 1978;2:429-44.

[149] Seiford LM, Thrall RM. Recent developments in DEA: The mathematical programming approach to frontier analysis. Journal of Econometrics. 1990;46:7-38.

[150] Lewis HF, Mallikarjun S, Sexton TR. Unoriented two-stage DEA: The case of the oscillating intermediate products. Eur J Oper Res. 2013;229:529-39.

[151] Banker RD, Thrall RM. Estimation of returns to scale using data envelopment analysis. Eur J Oper Res. 1992;62:74-84.

[152] Sexton TR. The methodology of data envelopment analysis. New Directions for Program Evaluation, Special Issue: Measuring Efficiency: An Assessment of Data Envelopment Analysis. 1986;1986:7-29.

[153] Sexton TR, Silkman RH. Data envelopment analysis: Critique and extensions. New Directions for Program Evaluation, Special Issue: Measuring Efficiency: An Assessment of Data Envelopment Analysis. 1986;1986:73-105.

[154] Lewis HF, Sexton TR. Data envelopment analysis with reverse inputs and outputs. J Prod Anal. 2004;21:113-32.

[155] Sexton TR, Mallikarjun S, Lewis HF. Hyperbolic DEA. 2012.

[156] Charnes A, Cooper WW, Ferguson RO. Optimal Estimation of Executive Compensation by Linear Programming. Manage Sci. 1955;1:138-51.

[157] Charnes A, Cooper WW. Management models and industrial applications of linear programming. New York,: Wiley; 1961.

[158] Zeleny M. The Pros and Cons of Goal Programming. Comput Oper Res. 1981;8:357-9.

[159] Min H, Storbeck J. On the Origin and Persistence of Misconceptions in Goal Programming. J Oper Res Soc. 1991;42:301-12.

[160] Lund J, Sanner B, Rybach L, Curtis R, Hellstrom G. Geothermal (Ground-Source) Heat Pumps: A world Overview. GHC BULLETIN2004.

[161] Ozgener O, Hepbasli A. Modeling and performance evaluation of ground source (geothermal) heat pump systems. Energ Buildings. 2007;39:66-75.

[162] Lienau PJ, Lunis BC. Geothermal direct use engineering and design guidebook. 1991. p. Medium: ED; Size: Pages: (445 p).

[163] Perez-Lombard L, Ortiz J, Pout C. A review on buildings energy consumption information. Energ Buildings. 2008;40:394-8.

[164] EIA USEIA. Annual Energy Outlook 2013. In: Energy USDo, editor. Washington, DC: Office of Integrated and International Energy Analysis; 2013.

[165] Aigner DJ, Sorooshian C, Kerwin P. Conditional demand analysis for estimating residential end-use load profiles. The Energy Journal. 1984;5:81-98.

[166] Marceau ML, Zmeureanu R. Nonintrusive load disaggregation computer program to estimate the energy consumption of major end uses in residential buildings. Energ Convers Manage. 2000;41:1389-403.

[167] Iniyan S, Sumathy K. An optimal renewable energy model for various end-uses. Energy. 2000;25:563-75.

[168] Murray A, Tonjes D. Energy Assessment of Smithtown, New York. Journal of Urban Technology. 2013;20:81-98.

[169] Koomey JG, Martin NC, Brown M, Price LK, Levine MD. Costs of reducing carbon emissions: US building sector scenarios. Energy Policy. 1998;26:433-40.

[170] Silveira JL, Gomes LA. Fuel cell cogeneration system] a case of technoeconomic analysis. Renewable and Sustainable Energy Reviews. 1999;3:233-42.

[171] Moura PS, de Almeida AT. The role of demand-side management in the grid integration of wind power. Appl Energ. 2010;87:2581-8.

[172] Ramotowski MJ, Klassen MS, Eskin LD, Roby RJ. Burn biofuels in gas turbines with improved heat rate and natural gas level emissions. PowerGen International, Orlando, FL. 2008.

[173] Rabago KR. Strategy for Developing Stationary Biodiesel Generation, A. Cumb L Rev. 2005;36:461.

[174] Energy.Information.Administration. Inventory of Nonutility Electric Power Plants in the United States 2000. Washington DC: Office of Coal, Nuclear, Electric And Alternate Fuels; 2003.

[175] Alshuwaikhat HM, Abubakar I. An integrated approach to achieving campus sustainability: assessment of the current campus environmental management practices. Journal of Cleaner Production. 2008;16:1777-85.

[176] Bernheim A. How green is green? Developing a process for determining sustainability when planning campuses and academic buildings. Planning for Higher Education. 2003:99-110.

[177] Scheuer C, Keoleian GA, Reppe P. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energ Buildings. 2003;35:1049-64.

[178] Shah VP, Debella DC, Ries RJ. Life cycle assessment of residential heating and cooling systems in four regions in the United States. Energ Buildings. 2008;40:503-13.

[179] University.of.Texas. Power Plant Equipment. 2014.

[180] University.of.Texas. Campus Energy Data. 2014.

[181] Katzenstein W, Apt J. Air emissions due to wind and solar power. Environmental Science & Technology. 2008;43:253-8.

[182] The.Univerisity.of.Iowa. Utilities&Energy.Management. 2014.

[183] Iowa.Energy.Center. Renewable Energy - Wind. 2014.

[184] Iowa.Energy.Center. Renewable Energy - Biomass. 2014.

[185] Stony.Brook.University. Central Heating and Cooling Plants. 2014.

[186] Renewable.Energy.Long.Island. Windworks. 2014.

[187] Renewable.Energy.Long.Island. Solar Thermal. 2014.

[188] Stanford.Sustainability&Energy.Management. Center Energy Facility. 2014.

[189] Stanford.Sustainability&Energy.Management. Stanford's Energy Story. Stanford, California: Stanford University; 2010.

[190] EIA. Modeling distributed generation in the buildings sectors. Washington D.C.: U.S. Department of Energy; 2013.

[191] Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-Geiger climate classification. Hydrology & Earth System Sciences Discussions. 2007;4.

[192] E.I.A. Commercial Building Energy Consumption Survey, Energy End-Uses. Oct 2008 ed2008.

[193] EnergyStar. Portfolio Manager Technical Reference: U.S. National Energy Use Intensity. Department of Energy; 2014.

[194] U.S. Department of Energy D. Buildings Energy Data Book. Energy Efficiency & Renewable Energy; 2014.

[195] StonyBrook.University.Medical.Center. Fact & Stats. Stony Brook University: Office of Communication; 2009.

[196] Simon. Smith Haven Mall. Indianapolis, Indiana: Simons Property Group; 2006.

[197] Lam JC, Li DH. Electricity consumption characteristics in shopping malls in subtropical climates. Energ Convers Manage. 2003;44:1391-8.

[198] Marriot. Long Island Marriot Marriot Hotels & Resorts; 2014. p. Hotel Details.

[199] Deng S-M, Burnett J. A study of energy performance of hotel buildings in Hong Kong. Energ Buildings. 2000;31:7-12.

[200] Canon. Canon U.S.A Celebrates Official Grand Opening of its Canon Americas Headquarters with Chairman and CEO of Canon Inc. and Local Officials. Melville, New York2013.

[201] Cole RJ, Kernan PC. Life-cycle energy use in office buildings. Build Environ. 1996;31:307-17.

[202] Bridges E, Coughlan AT, Kalish S. New technology adoption in an innovative marketplace: Micro-and macro-level decision making models. International Journal of Forecasting. 1991;7:257-70.

[203] Stewart F, Ranis G, Thomas H, Wilde Td. Macro-policies for appropriate technology: synthesis of findings. The other policy: the influence of policies on technology choice and small enterprise development: Intermediate Technology Publications; 1990. p. 3-42.

[204] Nemet GF. Demand-pull, technology-push, and government-led incentives for non-incremental technical change. Research Policy. 2009;38:700-9.

[205] Zmud RW. An examination of “push-pull” theory applied to process innovation in knowledge work. Manage Sci. 1984;30:727-38.

[206] Geser H. Towards a sociological theory of the mobile phone. Springer; 2004.

[207] Gross D. Forbes greatest business stories of all time. New York: J. Wiley & Sons; 1996.

[208] Pyper J, ClimateWire. Are Microgrids the Answer to City-Disrupting Disasters? . Scientific American. Energy & Sustainability2013.

[209] Kumagai J. The Rise of the Personal Power Plant. IEEE Spectrum2014.

[210] Pyper J, ClimateWire. Tiny Electric Grids Help States Weather Extreme Storms. Scientific American. Energy & Sustainability2014.

[211] Quality OoTaA. Gas Guzzler Tax. In: Agency USEP, editor.2012.

[212] Frey BS, Jegen R. Motivation crowding theory. Journal of economic surveys. 2001;15:589-611.

[213] Coad A, de Haan P, Woersdorfer JS. Consumer support for environmental policies: An application to purchases of green cars. Ecol Econ. 2009;68:2078-86.

[214] Hadjipaschalis I, Poullikkas A, Efthimiou V. Overview of current and future energy storage technologies for electric power applications. Renewable and Sustainable Energy Reviews. 2009;13:1513-22.

[215] Hall PJ, Bain EJ. Energy-storage technologies and electricity generation. Energ Policy. 2008;36:4352-5.

[216] Barton JP, Infield DG. Energy storage and its use with intermittent renewable energy. Energy Conversion, IEEE Transactions on. 2004;19:441-8.

[217] Grübler A, Nakićenović N, Victor DG. Dynamics of energy technologies and global change. Energ Policy. 1999;27:247-80.

[218] Demirbas A. Importance of biodiesel as transportation fuel. Energ Policy. 2007;35:4661-70.

[219] Howarth RW, Ingraffea A, Engelder T. Natural gas: Should fracking stop? Nature. 2011;477:271-5.

[220] Carrette L, Friedrich K, Stimming U. Fuel cells–fundamentals and applications. Fuel cells. 2001;1:5-39.

[221] Barbir F. PEM fuel cells: theory and practice: Academic Press; 2013.

[222] Shao Z, Haile SM. A high-performance cathode for the next generation of solid-oxide fuel cells. Nature. 2004;431:170-3.

[223] Steele BC, Heinzel A. Materials for fuel-cell technologies. Nature. 2001;414:345-52.

[224] Venkataraman C, Habib G, Eiguren-Fernandez A, Miguel A, Friedlander S. Residential biofuels in South Asia: carbonaceous aerosol emissions and climate impacts. Science. 2005;307:1454-6.

[225] Demirbas A. Biofuels sources, biofuel policy, biofuel economy and global biofuel projections. Energ Convers Manage. 2008;49:2106-16.

[226] Melillo JM, Reilly JM, Kicklighter DW, Gurgel AC, Cronin TW, Paltsev S, et al. Indirect emissions from biofuels: how important? Science. 2009;326:1397-9.

[227] Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, et al. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science. 2008;319:1238-40.

[228] Wetterlund E, Leduc S, Dotzauer E, Kindermann G. Optimal use of forest residues in Europe under different policies—second generation biofuels versus combined heat and power. Biomass Conversion and Biorefinery. 2013;3:3-16.

[229] Ahrenfeldt J, Thomsen TP, Henriksen U, Clausen LR. Biomass gasification cogeneration–A review of state of the art technology and near future perspectives. Appl Therm Eng. 2013;50:1407-17.

[230] Denholm P, Margolis RM. Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems. Energ Policy. 2007;35:2852-61.

[231] Katiraei F, Aguero JR. Solar PV integration challenges. Power and Energy Magazine, IEEE. 2011;9:62-71.

[232] Romero M, Steinfeld A. Concentrating solar thermal power and thermochemical fuels. Energy & Environmental Science. 2012;5:9234-45.

[233] Thirugnanasambandam M, Iniyan S, Goic R. A review of solar thermal technologies. Renewable and Sustainable Energy Reviews. 2010;14:312-22.

[234] Raisul Islam M, Sumathy K, Ullah Khan S. Solar water heating systems and their market trends. Renewable and Sustainable Energy Reviews. 2013;17:1-25.

[235] Chan H-Y, Riffat SB, Zhu J. Review of passive solar heating and cooling technologies. Renewable and Sustainable Energy Reviews. 2010;14:781-9.

[236] Phetteplace G. Geothermal heat pumps. Journal of Energy Engineering. 2007;133:32-8.

[237] Self SJ, Reddy BV, Rosen MA. Geothermal heat pump systems: Status review and comparison with other heating options. Appl Energ. 2013;101:341-8.

[238] Mallikarjun S, Lewis HF, Sexton TR. Operational performance of US public rail transit and implications for public policy. Socio-Economic Planning Sciences. 2014;48:74-88.