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以薛普利值為基礎公用電網與微電網間電力交換之對價計算

Shapley Value-based Payment Calculation for Energy Exchange between Micro- and Utility Grids

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摘要

近年來，微電網間的整合發展改善了電力系統的效能以及提供經濟、可靠且持續性的電力供輸。其特徵在於以單一可控制的整體來管理相較於現有的電力系統會帶來一些好處，並且需要在微電網與其托管事業間聯合操作和共享利益。然而，為了提高和分享兩者間藉由電力交換帶來的效益，如何公平的計算單一個體在聯合操作中的成本分配以及補償是一個重要的議題。

本論文主要探討如何在微電網與其公用電網聯合操作時，透過能量的交換來最小化每日的發電成本。本文提出一個用來補償能量交易的支出計算方法，而能量的交易係基於縮減後的發電成本之公平分配。儘管公用電網和微電網是彼此連接運作的發電系統，本研究假設它們各自的發電量與負載仍然與其獨立運作時相當。我們以合作對局理論的薛普利值設計使電力交換聯盟節省發電成本的誘因，並提出參考獨立發電成本與聯合發電成本之能量交易支出計算方法。

我們根據微電網和公用電網個別擁有的發電單位，在無電力交換的情況下計算“as if”的獨立發電成本。為了計算微電網的每日發電成本，我們將機組發電量(UC)和經濟調度(ED)規劃為一個取決於固定配置的分佈式發電，一種可再生能源的來源與儲存系統的混合整數規劃問題。對於電力公司的發電成本，我們採用了可用機組在不同負載量下的每小時發電成本函數可透過機組發電量和經濟調度取得的聚合機組。

為了盡量減少與電網之間的電力交換的發電成本，我們提出了一個理想的集中式決策模型，其中微電網和其託管效用的產生都集中調度。通過利用獨立和聯合發電成本，我們計算聯合儲蓄和運用薛普利值模型，基於個人邊際成本對電力交換聯盟的貢獻，分配微型和公用電網之間的降低系統發電成本。為了公平地補償能量交換，我們計算以薛普利值和每個網格在聯合發電下實際發電成本的差值作為支付電力交易。

透過德州奧斯汀微電網與台灣電網間的互動模型，我們展現了理想狀況下，集中式決策電力交換模式降低了系統成本；並且建立了微電網與電廠間，發電盈餘能公平共享的對價基礎。為了能在夏季與冬季，系統皆能皆創造並共享每日發電盈餘，我們採用了基於薛普利值的對價計算模型，針對電力交換雙方各自所貢獻的盈餘做等價交換，以刺激微電網與電廠間的合作，進一步結合為集中化市場統合者下的可控制整體。

Abstract

In recent years, microgrids developed as an integral to improve power systems and provide an affordable, reliable, and sustainable supply of electricity. Each microgrid is managed as a single controllable entity with respect to the existing power system but demands for joint operation and sharing the benefits between a microgrid and its hosting utility. This thesis focuses on the joint operation of a microgrid and its hosting utility which cooperatively minimizes daily generation costs through energy exchange, and proposes a payment calculation scheme that compensates for power transactions based on a fair allocation of reduced generation costs.

This research assumes that although the utility and the microgrid are operating as interconnected power systems, they have their own generation and loads and are still able to undergo standalone operations. To incentivize generation cost savings that can be realized by a power exchange coalition, we adopt the cooperative game theoretic solution concept of Shapley value and suggest a fair payment calculation scheme for power transactions which requires the evaluation of standalone and joint generation costs.

Our approach first calculates the “as-if” standalone generation cost for both the micro- and the utility grids based on the minimized cost of their individually owned generation units with no power exchange. To calculate the microgrid’s daily generation

costs, we formulate its unit commitment (UC) and economic dispatch (ED) as a mixed integer programming problem given a fixed configuration of distributed generation, a renewable energy source and an energy storage and apply a commercial solution package. As for the utility grid's generation cost, we model it as an aggregated unit, of which the hourly generation cost function for the available generation units over different load levels has been given.

To minimize the generation costs with power exchange between the grids, we then propose an ideally centralized decision model where the generation of the microgrid and its hosting utility are jointly dispatched. By exploiting the standalone and joint generation costs, we calculate joint savings and apply the model of Shapley value to distribute reduced system generation cost between the micro- and utility grids based on their individual marginal cost contributions to the power exchange coalition. To fairly compensate for energy exchange, we calculate the payments for mutual power transactions as the difference of the Shapley values and the actual generation cost of each grid under joint generation.

We design a fictitious interconnection model between the Mueller microgrid in Austin, Texas and the utility grid in Taiwan for case study to share the savings from their coalition through fair payments for energy exchange. Our case study shows that compared to standalone generation, both the micro- and utility grids are better-off when they collaborate in power exchange regardless of their individual contributions to the power exchange coalition. Fair payments for both a summer and winter generation scenario, however, show that joint savings through energy exchange depend on variations in load profiles and ask for different cost reimbursement schemes during summer and winter. To incentivize sharing the savings from energy exchange, we compensate microgrid saving contributions from solar power and distributed generation during summer by utility to microgrid payments, and mutually beneficial energy exports from the utility to the microgrid during winter by microgrid to utility payments.

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Chapter 1

Introduction

1.1 Motivation

The integration of changing technologies and new entrants in the generation market requires major changes in the operations of the electricity market to become smarter in order to provide an affordable, reliable, and sustainable supply of electricity. [Hog93] [Li10] To enhance the reliability and reduce the costs of an integrated transmission grid, the smart grid concept has encouraged researchers to study ways of generating power locally in proximity to the customer through combining together loads and distributed generation (DG) in so called microgrids. [HVN11] [CCC09] [Hat07]. A microgrid is a network of small-scale distributed energy resources (DER) such as solar panels, wind turbines, fuel cells and micro-turbines that can either operate standalone or interconnected to the utility grid. Its feature to be managed as a single controllable entity with respect to the existing power system poses several benefits, and demands for joint operation models with the utility network.

An energy exchange scheme for the joint operation of a microgrid and a utility network exploits diversity features to gain and share benefits from cooperative generation; among others the possibility to reduce system operation costs through access to linked generation resources which may improve generation decisions. [Bay14]

[AwP12] For the operation of interconnected power systems, power pools were introduced to group existing generating plants and jointly dispatch them to operate the short-term market. [Hog93] Pooling systems provide a proper basis for operating cost allocation and can help to derive an equitable method for cost reimbursement and benefit allocation. [YuD96] Generally, an independent service operator (ISO) or brokerage system is responsible for the market coordination of joint operation decisions and provides many services implicit in the economic dispatch.

Game theory often is applied here to understand the participants' behaviors of a power transaction game. In a power transaction game, participants' transactions are modeled as a game of strategies in which participants compete to maximize their payoffs. Saad et al. provides a clear overview on the recent developments in game theory for microgrids particularly with respect to coalition formation games. [SHP12] [SHP11]

Another central question is how to distribute the costs and benefits of a joint effort among the participants in a power transaction game. For the power market environment, cost allocation has especially been applied in utilities to help address emission trading and transmission expansion planning [Cha95] [CoW99]. The Shapley value criterion is commonly used here as a solution concept for the allocation of cost savings among the utilities. [Cha95] [CoW99] The Shapley value is perhaps the most commonly used method to allocate the costs in cost sharing games as it is budget-balanced and guarantees equilibrium existence in any game regardless of its parameters. [GMW11]

Its favorable properties to support a mutually agreeable division of costs motivated its usage to suggest a payment calculation scheme for the joint operation of a microgrid and a utility with energy exchange on the basis of fairly distributed joint operation costs in the succeeding of this thesis. The motivation of a payment calculation scheme for the energy exchange between a microgrid and its hosting utility is illustrated in Figure 1. Daily payments for mutual power transactions are calculated regarding the individual grids cost and generation contribution while jointly adducing an aggregated load schedule.

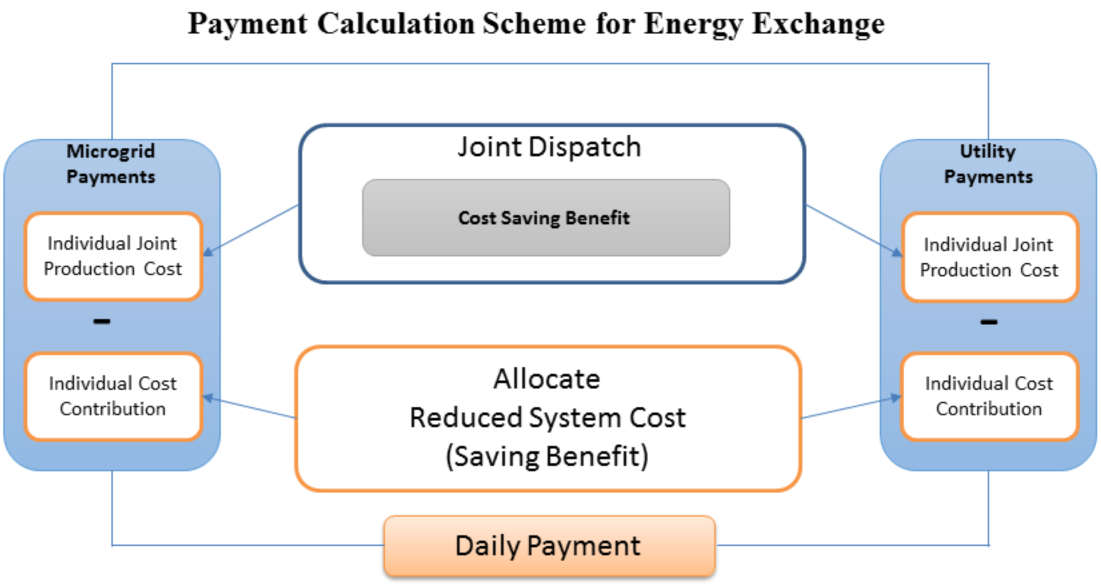

Figure 1. Payment Calculation Scheme for Energy Exchange

1.2 Scope of Research

This thesis focuses on the joint operation of a microgrid and its hosting utility with the aim to cooperatively minimize daily generation costs through energy exchange and propose a payment calculation scheme that compensates for energy exchange based on fairly allocating joint operation costs. For this purpose, we assume a privately-owned microgrid which is interconnected to a hosting utility. In order to minimize daily generation cost (primarily fuel costs), each system has sufficient generation resources to meet its own loads, however, can make a decision on whether to operate standalone or in joint generation. In this regards, this study first (i) determines the daily generation costs from standalone operation for a microgrid and its hosting utility with no power exchange, then (ii) proposes a cost model for the joint operation with power exchange as a proper basis for generation cost allocation, and finally (iii) suggest a payment calculation scheme which compensates for energy exchange based on fairly allocating joint generation costs. In this regards, we adopt the cooperative game theoretic solution concept of Shapley value to fairly allocate reduced generation costs from joint operation and incentivize generation cost savings that can be realized when the micro- and utility grids form a coalition through mutual payments for energy exchange.

1. System Configuration and Standalone Cost Models

To calculate the individual generation costs from standalone grid operations, the decision model is inserted into the architecture of a single microgrid and a utility grid with fixed system configurations and deterministic input variables that consider their individual load profiles and generation constraints. Although many sources suggest additional criteria for the definition of microgrids, e.g. controllable loads, the ability to operate in islanding mode or combined heat and power (CHP), our study only concerns about the electric system of a microgrid with the aim to suggest a proper basis for operational cost sharing with the electric utility.

To calculate the microgrid's daily generation costs, we fit a quadratic cost curve to the cost characteristics of the distributed generation units and solve the optimal unit commitment and economic dispatch determined by a fixed configuration of distributed generation, a renewable energy source and an energy storage system as a mixed integer programming problem for every load level. For the utility's generation cost, we adopt an aggregated unit of which the hourly generation cost function for the available generation units over different load levels is obtained through unit commitment and economic dispatch and construct the utility's daily generation cost as proposed by Chang et al. [SCC90]

2. Joint Generation Cost Model

To cooperatively minimize short-term operation costs, we develop a cost model for the joint operation of a microgrid and its hosting utility with power exchange between the grids. Ideally, we assign a market coordinator with complete information to centrally dispatch available generation units and compute the optimal amount of energy traded when the grids act as one single entity. Since there is only one entity, our joint generation cost model represents the ideal case of adducing an aggregated load schedule without a profit margin for energy exchange and describes the best way to achieve joint cost savings between the micro- and utility grids.

3. Cost Allocation and Payment Calculation

By exploiting standalone and joint generation costs, we compare the cumulative cost from standalone dispatch with the cost under joint dispatch to calculate the reduced generation costs for the allocation of cost savings. We then apply the Shapley value to distribute the savings between the micro- and utility grids based on their individual marginal cost contributions to the power exchange coalition. Against the background of different cost contributions, the Shapley value function supports a division of joint operation costs in a coalition and helps to compensate for energy exchange by fairly calculating the payments for the energy exchange between the utility and the microgrid.

In summary, we set up a decision model to exhibit cost savings for the joint generation of a micro- and utility grid and adopt the Shapley value to suggest a payment calculation scheme which fairly compensates for energy exchange through payments for mutual power transactions. The contributions of this thesis are as follows.

1. Motivate payments for power transactions to gain benefits from energy exchange between a microgrid and its hosting utility (e.g. to reduce generation costs)
2. Formulate and solve the unit commitment (UC) and economic dispatch (ED) problem as a mixed integer programming for the microgrid and adopt an aggregated thermal unit to solve it for the utility
3. Set up a joint decision model for cooperatively minimizing daily generation cost through energy exchange where available generation units are ideally centralized dispatched to deliver an aggregated load schedule
4. Based on realized cost savings, adopt the game theoretic solution concept of Shapley Value to allocate reduced system operation cost and compensate for energy exchange through fair payments for power transactions
5. Conduct a case study for the fictitious operation of a microgrid and its hosting utility to demonstrate cost savings, calculate Shapley values and individual contributions to joint generation scheduling to evaluate fair payments for energy exchange for two different generation scenarios

1.3 Organization of Thesis

The remainder of this thesis is organized as follows. Chapter 2 serves as an introduction into the concept of microgrids and their participation in the electricity market. The operation modes, ownership models and possible forms of market participations are discussed behind the background of embedding microgrids into the existing power system. Further, the benefits and challenges from energy exchange between the microgrid and its extant power grid are pointed out. To evaluate the generation cost from standalone microgrid operations, the daily generation cost of microgrids without power exchange is studied and a decision model for optimal generation scheduling is formulated. After, the methodology is tested for an existing microgrid in Austin, Texas. Next, Chapter 4 formulates the standalone cost model for the utility and introduces the Taipower Company as the utility provider for our case studies. To provide a proper basis for generation cost allocation, Chapter 5 formulates a cost model for the joint generation between a microgrid and its hosting utility where generation is centrally dispatched to jointly deliver an aggregated load schedule. Afterwards, the model is tested for the interconnection between the Taipower Company and the Mueller microgrid to present some results. Finally, Chapter 6 allocates the costs from joint generation by applying the Shapley value and fairly calculates the mutual payments between the Taipower Company and the Mueller microgrid based on a mutually agreeable allocation of joint operation costs. Chapter 7 concludes this thesis and lists some future work.

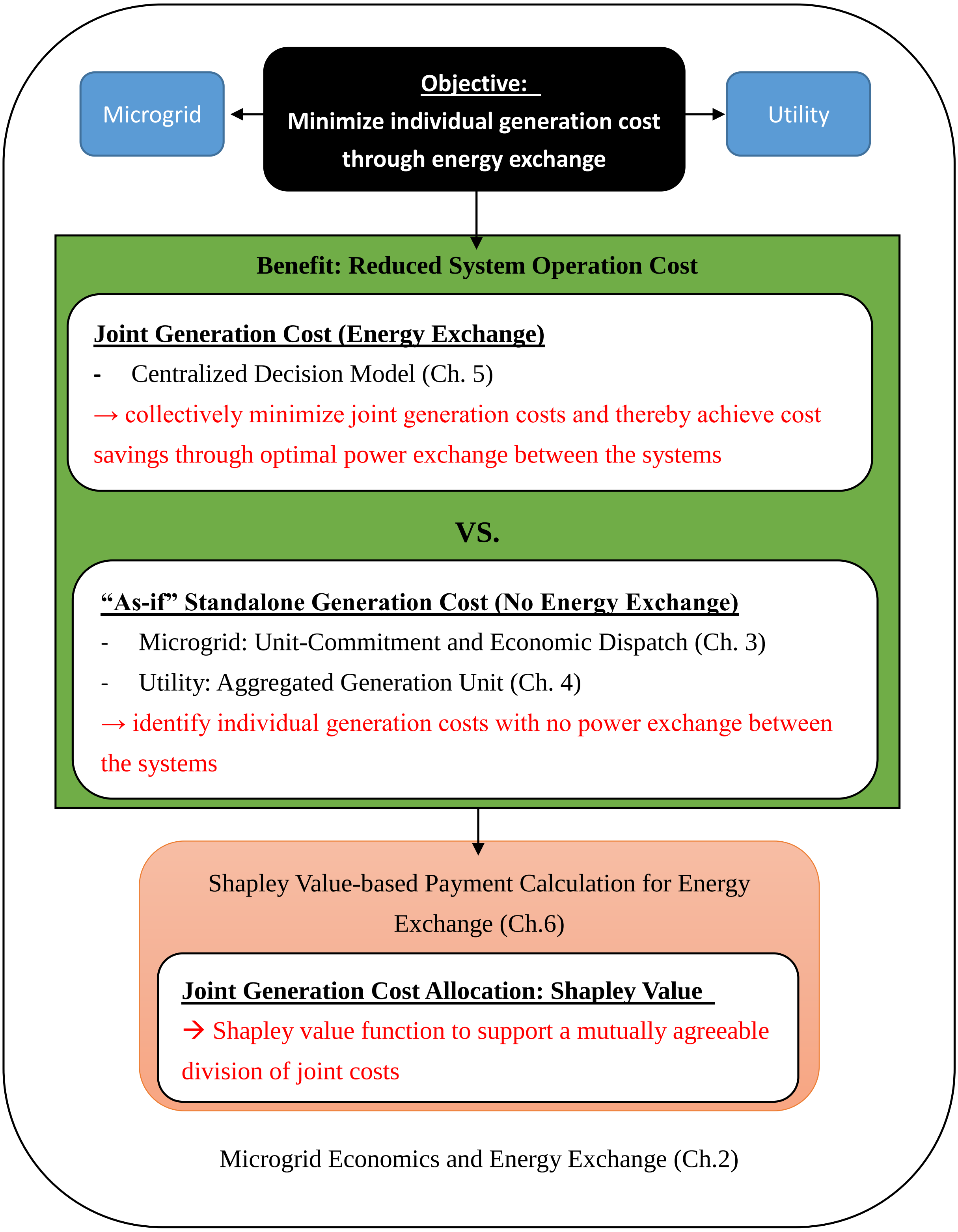

Figure 2. Organizational Flow Chart

Chapter 2

Microgrid Economics and Energy Exchange

2.1 Introduction to Microgrids

Conventionally, power systems which exploit efficiency gains from increasing generating capacity were established to distribute bulk power over long-distance transmission lines to location-specific demand centers that connect to their customers via distribution lines. However, the concerns about the increasing electricity demand and environmental pollution from central power plants ask for alternative ways in power generation: distributed generation. The term ‘distributed generation’ (DG) has been devised to describe the power generation from a localized grouping of distributed energy resources (DER) that are able to operate isolated or connected to the traditional utility grid in a way that creates efficiency gains from smaller generation capacities closely located to the sites of demand. [CCC09]

In this respect, microgrids that use smart network technologies promote a new concept to embed renewable energy sources and distributed generation into the existing distribution system. The U.S. Department of Energy (DOE) defines a microgrid as “a group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid [and can] connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.” [DOE11]

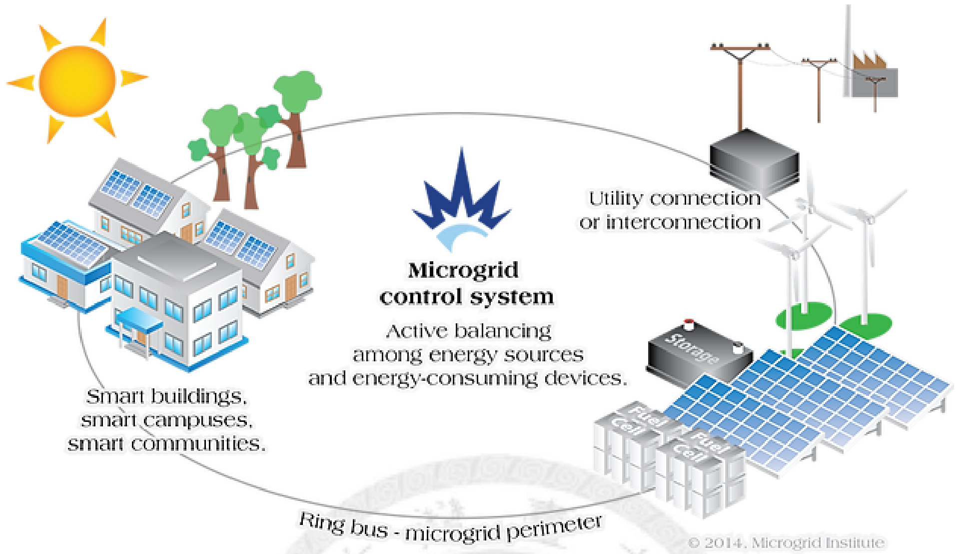

Figure 3. Simplified Microgrid Concept [MiI14]

As simplified in Figure 3, microgrid generation usually combines intermittent renewable energy sources (RES), dispatchable (co-)generation sources and storage devices connected through a low-voltage distribution network to meet the system loads. Available and currently developing technologies for distributed generation (DG) and distributed storage (DS) units commonly used in microgrids are:

(a) **Distributed generation technologies:** combustion engines, microturbine, wind turbines, fuel-cells, solar-thermal systems, photovoltaic systems, low-head hydro units and geothermal systems, and

(b) **Distributed storage technologies:** battery storage, capacitor storage, low- and high-speed flywheel, and superconducting magnetic energy storage systems.

2.1.1 Microgrid Operation Modes

A microgrid can operate either interconnected to the utility grid (interconnected microgrids) or isolated (standalone microgrids). [Sma02] [Hya10] Historically, standalone microgrids were established as power grids (e.g. for military operations, island communities or remote industrial sites) suitable for supplying power to remote areas where the supply for the national grid system was difficult to setup or frequently disrupted. As isolated microgrids don't allow power exchange with the utility grid, they typically include extra capacity with respect to the load for reasons of emergency generation and peak demand.

Conversely, interconnected microgrids are embedded into the distribution network and connected to the utility grid according to a predefined set of interconnection standards. IEEE 1547, for example, is a uniform standard for interconnection of distributed resources with electric power systems that provides requirements relevant to the performance, operation, testing, safety, and maintenance of the interconnection. [IEE09] As already mentioned, interconnected microgrids can have the ability to operate in two connection modes: (a) grid-connected and (b) islanding. In grid-connected mode, the microgrid stays connected to the utility grid either totally or partially in order to exchange energy. On the contrary, in 'islanding' mode it operates isolated from the grid. Islanding enables DG resources to disconnect from the utility and supply microgrid loads only with self-sufficient generation as in physical islands.

The Mueller Community in Austin, Texas is a demonstration project of an interconnected microgrid that operates together with the utility operator of Austin. Mueller's microgrid system includes a mix of residential and commercial loads, and distributed generation technologies including roof-mounted photovoltaic (PV) systems, water heaters, and a gas-fired CHP combustion turbine. [UrH13] The microgrid connects to the external grid and allows electricity and data exchange. Figure 4 shows a cartoon schematic of a single-family house in the Mueller Community that is interacting with the electric, gas, and water utilities. [RUM14]

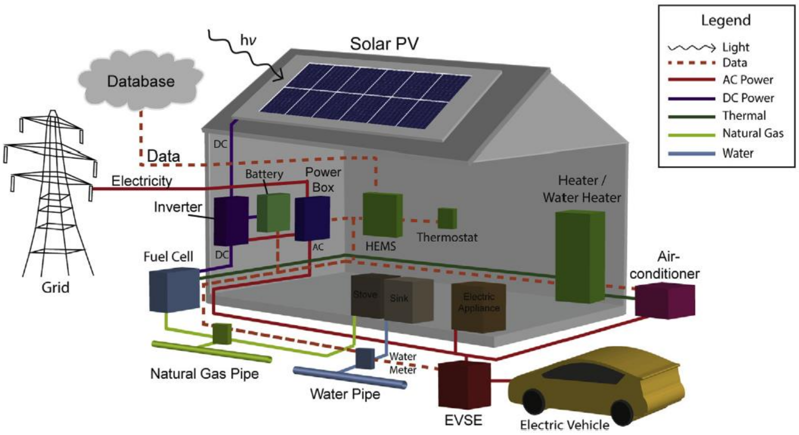

Figure 4. A cartoon schematic of a single- family house in the Mueller Community

2.1.2 Microgrid Ownership Models

According to a report of the New York State Energy Research and Development Authority (NYSEDRA), "the viability of a given microgrid within today's legal and regulatory structure depends on […] who owns the microgrid infrastructure […] and how profits from those services are earned.” [Hya10] To provide more information about the granularity of microgrid opportunities, the NYSREDA developed a framework for the ownership of physical and virtual microgrids following King and Driesen and Katiraei. [Hya10] Their conceptual framework distinguishes microgrids into as follows:

1. **Utility owned physical microgrids:** utilities either fully (i.e. vertically integrated) or partially (i.e. unbundled) own microgrids to improve local reliability, differentiate their services or to compete with non-utility microgrid service companies.
2. **Non-utility owned physical microgrids:** non-utility owned microgrids provide lower cost, more reliable and cleaner energy services, and have the potential to become a significant new area of investment for distributed energy services. Non-utility microgrid ownership models are based on whether the primary purpose is for self-service or for merchant service.
3. **Virtual microgrids:** a virtual microgrid is a distributed energy resource-pooling model that uses existing power systems (e.g. utility distribution infrastructures) to link multiple energy production resources and loads. Under a virtual microgrid scheme, locally sited energy resources supply multiple end users, but there is no separate physical connection between participating supply and loads.

2.1.3 Microgrid Market Participation

The integration of changing technologies and new entrants in the generation market requires major changes in the institutions and operations of the electricity market. In this regards, Hogan developed a model for the structure of the competitive electricity market which emphasizes open access to the transmission system as a necessary requirement for the development and operation of a competitive energy market. [Hog93] According to his work, improvements in the transmission market can help to assign the coordination of short-term operation decisions to a single coordination function which provides many services implicit in the economic dispatch to improve the power system e.g. through an independent system operator (ISO). [Hog93] Traditionally, vertically integrated utilities started to introduce power pools (e.g. NEPOOL, NYPOOL, PJM) to facilitate energy exchange and collaborative generation development.

In deregulated energy markets, generation resources are unbundled and customers are free to purchase from any supplier on the grid. Hence, restructuring can significantly increases the level of service reliability and reduce costs through improved economic efficiency. In order to achieve competitive electricity market goals, FERC has facilitated the development of three basic transaction models that can help microgrids to participate in a newly restructured open market: [CCC09]

1. **Centralized clearing market (PoolCo):** clears the market for buyers and sellers which submit bids to the pool for the amount of power that they are willing to trade. This introduces competition among the pool members by forcing them to generate so that operating costs are minimized. Based on their market bids, the most economic generation resources are centrally dispatched to adduce an aggregate load schedule. To establish an independent power pool served by an interconnected transmission systems, PoolCo does not own any generation or transmission components and only has central dispatch jurisdiction for its pool members.
2. **Bilateral Contracts Model:** Without regulation and open market access, transactions among the buyers and sellers can take place directly through bilateral contracts. Bilateral contracts allow buyers and sellers to negotiate directly in the electricity market without entering into pooling arrangement without a connector system. However, these transactions need to be evaluated ahead of their scheduling to check their feasibility with respect to system operating conditions.
3. **Hybrid model:** The hybrid model combines various features of both the pool market and bilateral contracts. Here the sale and purchase of power through a power exchange (PX) are not obligatory and the customers are allowed to sign

bilateral contracts with the pool suppliers of their choice. All the bilateral contracts are normally allowed unless the transmission lines are constrained. Loads that are not included in the bilateral contracts are supplied by economic dispatch of generators through bids in the pool. The co-existence of the pool efficiently identifies the energy requirements of the individual customers and thus helps to simplify the energy balance process.

2.2 Benefits of Integrating Microgrids into the Grid

Although utilities viewed microgrids with an amount of skepticism due to the fact that they posed a threat to utility revenues under traditional regulatory models [ABB], the deregulation of energy markets, public concerns about environmental pollution and decreasing costs of DG technologies pushed the integration of microgrids into the existing power system.

The microgrid market opportunity is primarily driven by a microgrids ability to reduce operation cost through improved system efficiency. [Nav06] Microgrids can significantly contribute to increase the penetration of renewables, reduced greenhouse gas emissions, and provide increased reliability and security for the power system. [CCC09] [Nav06] Navigant Research examined that the global market from the deployments of microgrids will be around $10 billion in 2013, and exceed $40 billion annually by 2020 with dozens of pilot programs launched globally. According to their report, the total worldwide capacity of distributed generation contained in microgrids will grow from 764 MW in 2012 to about 4,000 MW in 2018, valued at more than $12.7 billion in vendor revenues. [AsD10]

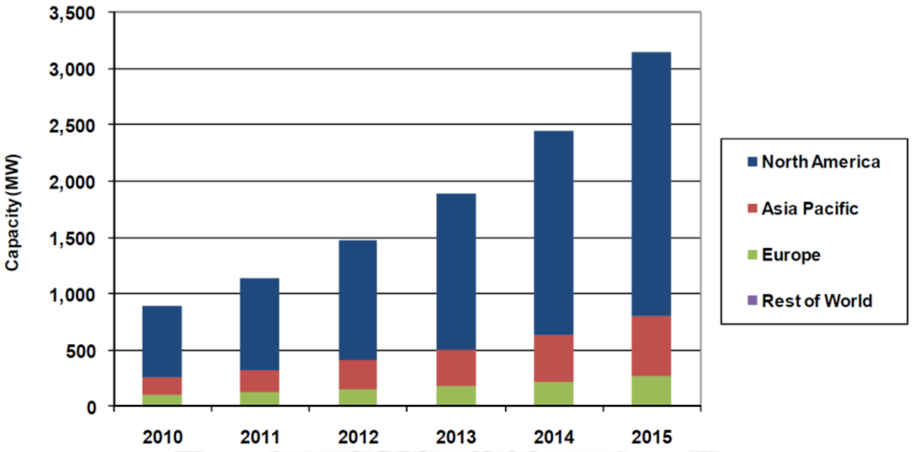

Figure 5. Microgrid Capacity, World Markets: 2010-2015 [AsD10]

2.2.1 Optimized Power Systems

Microgrids can significantly improve power quality and energy efficiency through effectively managing distributed energy resources controlled as one single entity which create new business opportunities in the open market. Market restructuring helps to integrate microgrids into the grid and create economic benefits from reduced cost and increased reliability. Microgrids participating in an open market environment create several value-added opportunities for the society, the grid, and its customers by linking technical and economic benefits. [Nav06] [Mor11]:

- **Autonomy:** Microgrids can deploy on-site distributed generation in conjunction with energy storage in an autonomous fashion to supply loads as single controllable entities with respect to the utility grid.
- **Compatibility:** Microgrids have ‘plug and play’ features to work in compatibility with the utility grid, and allow the expansion of the existing power system that help to create new revenues by maximizing the operation of utility assets.
- **Flexibility:** Microgrids increase the flexibility of existing power systems and reduce the cost of energy by utilizing a heterogeneous mix of distributed energy resources that optimize their location-specific, individual objective functions.
- **Stability:** Microgrids increase the reliability, resiliency and security of power systems by promoting demand response (DR) programs that reduce the load on the main grid and including control mechanism that allow the entire network to operate in a stable manner regardless of whether the main grid is up or down.
- **Energy-Efficiency:** Microgrids promote the deployment and integration of energy-efficient and environmentally friendly technologies which help to optimize economic and environmental energy management goals, and can help to contribute to higher total energy efficiency lowering the overall load baseline, reducing transmission and distribution costs and minimizing energy losses.

2.2.2 Opportunities from Energy Exchange

To cooperatively gain benefits from energy exchange, microgrids need to participate in energy transactions with their hosting utilities that can facilitate integrated system operations. The joint operation of a microgrid and its hosting utility can improve economies of scale by expansion of operational regions through interconnection of generation and making the best use of available resources.

Referring to Bayram et al. [Bay14], the microgrid benefits from energy exchange can be summarized as following:

- **Reduced system operation cost and peak-to-average demand ratios:** Utilities dispatch their generation portfolio in order to meet the customer loads through large-scale, low-cost generators that meet base load demands first and dispatch more generators with increasing minute-by-minute varying customer demands. Fast-start, high cost generators accommodate electricity demand during peak hours that account for approximately 10% of the day. During the peak hours, the system operation cost increases exponentially. The concept is illustrated in Figure 6. Microgrid energy exchange helps to reduce the peak-to-average demand ratio by locally trading energy during peak hours and will benefit in the form of cost savings.

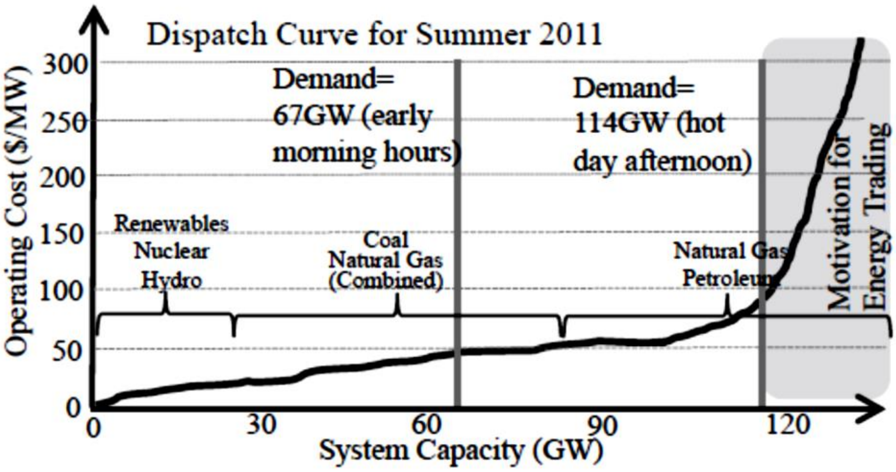

Figure 6. Electric Power Generation Cost [Bay14]

- **Improved system efficiency and decentralized power grid operations:** Microgrids use small-scale distributed generation and storage to improve the efficiency of power generation. [CCC09] [BCC11] The possibility of energy exchange encourages their integration as it allows energy mismatch management to balance supply and user demand locally in a decentralized fashion to reduce the reliance on high capacity generation options and congestions on transmission lines which enhances the reliability of the total system.

- **Reduced greenhouse gas (GHG) emissions and other pollutants:** Power grid operations account for one fourth of the global (GHG) emissions. To reduce emissions, a higher penetration of renewable energy sources and distributed energy generation realized encourages electricity trade with microgrids during peak hours, thereby improves the overall system efficiency and further helps to recycle wasted heat for heating, cooling and refrigeration through CHP systems installed in microgrids. It is assumed that such utilization can improve overall “energy efficiencies” by around 50% with additional reductions in per capita CO2 emissions. [Bal10] [PaH08]

2.2.3 Cost Saving Benefits from Joint Operations

Microgrid helps to balance demand and supply at smaller granularity than traditional power grids by cost-effectively using networks of relatively small local generators that allow collaboration in the electricity enterprise. [Bay14] Similar to utilities which traditionally formed power pools to jointly dispatch their generation resources and thereby achieve cost savings, the potential of microgrids is greatest when they can work together as virtual grids under the coordination of an independent market coordinator in the open market. [Hya10]

Hence, energy exchange between microgrids and their hosting utilities can create new business models through cooperating generating units and correctly allocating arising benefits from cooperation. As a result, several cost savings may arise for both the utility and the microgrid from collectively optimizing a variety of different cost types. This may include the following cost components:

(a) **Operation cost:** Generators have different marginal costs of generation, costs for start-up and shut-down, and ramp-up costs. As described before, utilities mainly dispatch low-cost generators to meet base load demands but dispatch more expensive generators with increasing minute-by-minute varying customer demands. Therefore, collectively optimizing microgrid and utility generators through energy exchange can lower generation costs and reduce peak-to-average demand ratios by trading-off different short-term operation costs.

(b) **Risk and cost of reliability:** Microgrids can reduce outage risks to critical loads by disconnecting from the main grid in the event of a fault or by turning off dispatchable loads. Often they also provide emergency power ancillary services to the main grid potentially including spinning and non-spinning reserves, voltage and frequency regulation, and black start support. [Mor12] Thus, energy exchange can increase the reliability of power provided to customers within and outside the microgrid with reduced cost of reliability.

(c) **Investment cost:** Microgrids help to improve energy efficiency through integrating DER which can reduce peak loading, environmental pollution and energy loss during distribution. [CCC09] As both the utility and microgrids themselves benefit from improved power systems, investment costs can be shared and jointly optimized.

(d) Transmission cost: The integration of microgrids helps to reduce distribution losses through lower line losses mainly because of the proximity of loads and supply in microgrids. Thus, embedding microgrid systems into the traditional power system can help to globally reduce transmission line usage and installation.

(e) Emission cost: Renewable energy sources and natural gas-fired CHP in microgrids produce power with significantly lower emission of GHGs and other pollutants compared to traditional power systems by integrating clean energy sources into the grid, and thus can reduce global cost from emission and other pollutants.

2.3 Challenges for the Joint Operation of a Microgrid and its Utility

To cooperatively gain and share the benefits from joint operations of a microgrid and its hosting utility, it becomes necessary to design a proper basis for the allocation of operational cost savings. Usually, an independent market coordinator which jointly dispatches available generation resources and fairly allocates joint costs to their individual cost contributions is needed. As a result, main difficulties from joint operation occur from determining relevant cost types, identifying joint operation schedules, and sharing costs associated with those operations.

2.3.1 Cost Evaluation in Microgrids

The value of a generation portfolio not only depends on its ability to correctly dispatch available generators to minimize operation cost but also needs to consider long-term operating decisions that involve investments, cost for transmission wires and reliability concerns.

For a microgrid, valuations in the short-run are based on the investment payoff directly linked to the optimal operation its generation assets. [FLK13] In this regards, most of the decision methods applied to short-run microgrid operations that can be found in literature are deterministic and find the minimized operation costs for a given set of technologies and a specific dispatch scenario. [Haw10] Conversely, in the long-run it also becomes necessary to predict the demand, intermittent generation of renewable energy and electricity prices in order to optimally utilize the installed microsources subject to market conditions and technical constraints. [FLK13] In the long-run basically two additional dimensions add to the valuation of a microgrids: the optimal selection of generators that take into account investment costs related to fuel and market prices [Haw10] and costs of meeting the demand with a degree of reliability that is appropriate for the value of load being served [BiA96] Long-term evaluations require advanced decision methods that account for uncertainties and may require extensive risk based decision making processes for operational strategies. [RaH09]

2.3.2 Trading Framework for Energy Exchange

Electricity trading frameworks that encourage the collaboration in demand dispatch are needed to facilitate energy exchange and allow microgrids to participate as a single controllable entity in the overall electricity market. [Bay14] As discussed in Chapter 2.1.3, there are different transaction models which have involved to achieve competitive electricity market goals and help microgrids to participate in the open market. To cooperatively gain and share the benefits from joint operation of a microgrid and its hosting utility three inter-related issues need to be addressed by market coordinators.

(a) **Joint planning problem:** choose among joint operation schedules that maximize the objective from cooperating generation units through side payments e.g. from sharing their utilities

(b) **Coalition formation problem:** deliver an aggregated load schedules by a coalition of distributed energy resources as an integrated power network

(c) **Cost allocation problem:** determine a rule that compares the outcomes from independent generation and cooperative generation, and fairly distributes the total surplus generated from joint operation among all generating units within a cooperation

In this regards, game theory serves an important analytical tool to study complex interactions in a power transaction game. In a power transaction game, participants' transactions are modeled as a game of strategies in which participants compete to maximize their payoffs. Any subset of participants is called a coalition, with a grand coalition representing all participants. A coalition may be constituted by one participant maximizing its payoffs. Saad et al. provides an overview on recent developments in game theory for microgrids particularly with respect to coalition formation games in microgrids. [SHP12] [SHP11]

More specifically, three comprehensive categories that employ different mathematical frameworks are used to solve the energy exchange problem: [Bay14]

(a) **Decentralized Solutions:** employ (1) auction mechanism to find the lowest-cost matching between the supply and demand to maximize the economic efficiency, (2) Stackelberg games to models the behavior of two agents with a leader and a follower or (3) non-cooperative games for the interaction among independent and self-interested agents.

(b) **Centralized Solutions:** are based on single objective maximization to compute the optimal amount of energy traded. Trading agencies act as one entity or controlled by a central controller who is assumed to know all the information about buyers and sellers.

(c) **Simulation-based Solutions:** use simulation-based optimization (SBO) to model the long-term behavior of multi scale decision making agents by making use of statistical learning algorithms such as reinforcement learning, Q-learning or Markov Decision Processes (MDP) so that trading agents can derive long-term profit making policies in an autonomous way.

2.3.3 Cost Allocation

As discussed in Sections 2.1.3 and 2.3.2, the potential of microgrids is greatest when they can participate in the open market and cooperatively dispatch generators through trading frameworks that allows power transactions. As just mentioned, different mathematical frameworks help to allow energy trading to maximize the benefits from delivering an aggregated schedule depending on their objective functions considering (a) the load profiles of both systems, (b) the cost curves of each generator, and (c) the economic dispatch of each generator in each period of load.

Notwithstanding, a major obstacle still constitutes the application of a cost sharing rule between the microgrid and the utility grid that supports the joint cost optimization based on their individual cost contributions, and fairly shares potential cost savings when the networks cooperate as a single unit. A well-known solution concept for cost sharing was introduced by Shapley, and is known as the Shapley value. [Sha53] The

Shapley value function helps to determine and fairly distribute the total surplus generated by all players in a cooperative game. In recent years, the theoretical analysis to develop criteria and methods for solving the cost sharing problem emerged as the field of cost sharing games in cooperative game theory. The methods to define and solve cost sharing games are summarized by Jain and Mahdian. [JaM07]

Chapter 3

Evaluation of Microgrid Generation Costs from Standalone Operation

This chapter calculates the “as-if” standalone costs for the microgrid based on the minimized cost of its individually owned generation units and assumes no power exchange with its hosting utility. Therefore, the daily generation cost of the microgrid is modelled as mixed-integer programming which is determined by the microgrid’s loads and a fixed configuration of solar panels, a combustion turbine for distributed generation, and PHEVs as controllable storage devices.

The results are then compared to the joint operation of the microgrid and its hosting utility which cooperatively minimize and fairly share daily generation costs with power exchange.

3.1 Introduction

As discussed in Chapter 2, decision models for standalone microgrids are mainly concerned about minimized fuel consumption, reliable operation and the assessment of renewable energy viability. [Tas09] In addition to the integration of distributed generation and renewables, different types of distributed energy storage may also be employed to store excess renewable power generation. [CGW12] [Zha13] Storage can help to mitigate risks from energy imbalances and make microgrids a stronger coupling system in the time domain. [Liu10] In recent years, especially the development of plug-in hybrid electric vehicles (PHEVs) created new opportunities for microgrid storage through vehicle-to-grid (V2G) power. [KeT05]

Although many research exist on unit commitment problems for the economic design and generation scheduling in microgrids, economic evaluation methods that quantify the costs and benefits are needed. In this regards, Morris presents a general method for evaluating key impacts, benefits, and stakeholders, and relating them to each other in a scalable, modular structure is proposed. [Mor12] Unlike standard dispatch models, the work presents a framework for the evaluation of costs and benefits in microgrids by introducing function parameters that capture the diversity of general microgrid characteristics including their objectives. Along with a framework for the evaluation of the costs and benefits of microgrids, a model for the discussion about how generation costs should be divided among different agents that benefit from the operations of a microgrid is needed [CoM09].

3.2 Problem Formulation

This section presents a cost model for the evaluation of daily generation in a standalone microgrid for the specific dispatch scenario of a summer and a winter day.

Therefore, our study describes the deterministic case of an optimization model with determined inputs. In this respect, the modelled microgrid produces power from a fixed installed capacity of intermittent renewable energy supply (i.e. solar power) and distributed energy resources (i.e. a gas turbine) to meet the loads demanded by the consumers. For the design of our cost model, renewable energy sources are indicated with zero marginal costs to make sure that renewable generation is fully dispatched. The aggregated power output from renewables is calculated to the effect of ambient conditions (i.e. solar irradiation) and treated as a negative load for any given load level. Excess renewable power is lost in cases where the output from renewable energy is greater than the load and no energy storage system available. Energy storage can help to store excess power and reduce distributed generation in future periods when installed. Therefore, a later extension of our model includes an energy storage system (ESS) to study the possible cost benefits with respect to the cost from distributed generation.

After determining the power output from renewable energy production, the remaining power output from distributed generation for each load level can then be determined. Distributed energy resources generate power whenever renewables are insufficient to fully serve the load. To reflect the actual generation costs, we use heat rate curves and fuel input prices to model their cost rate curves as a quadratic function following Wood and Wollenberg. [WoW12]

In the following, let us define some notations for the standalone microgrid.

Standalone microgrid cost model without storage

- Index/sets:

g	DG generating units
t	Time periods in 1-hour increments

- Parameters:

\- Cost functions

J ( )　Microgrid generation cost function

A_g	Constant from generation cost curve for DG unit g
B_g	First order component of generation cost curve for DG unit g
C_g	Second order component of generation cost curve for DG unit g

\- Power limits

$P_{g\,min}$	Minimum power level of DG unit g (MW)
$P_{g\,max}$	Maximum power level of DG unit g (MW)

- (Given) Forecasts:

$P_{R,t}$	Sum of power production from renewable energy supply (MW)
D_t	Power level demanded from the loads at time t (MW)

- Decision and logical variables:

$P_{g,t}$	Power generated by DG unit g in period t (MW)
$y_{g,t}$	Binary indicating if a DG unit g is on in period t

Standalone microgrid cost model with storage

- Index/sets:

g	DG generating units
s	Energy storage units
t	Time periods in 1-hour increments

- Parameters:

- Cost functions

J ( ) **Microgrid generation cost function**

Distributed Generation (DG)

A_g	Constant from generation cost curve for DG unit g
B_g	First order component of generation cost curve for DG unit g
C_g	Second order component of generation cost curve for DG unit g

- Power limits

Distributed Generation (DG)

$P_{g\,min}$	Minimum power level of DG unit g (MW)
$P_{g\,max}$	Maximum power level of DG unit g (MW)

Energy storage system (ESS)

η_c/η_d	Charging/discharging efficiency for energy storage system of type s
$E_{s\,max}$	Maximum capacity of energy storage system s (MWh)
$E_{s\,min}$	Minimum capacity of energy storage system s (MWh)
$P^{\mathrm{c}}{}_{s\,max}$	Maximum amount that can be added (charged) to storage (MW)
$P^{\mathrm{d}}{}_{s\,min}$	Maximum amount that can be withdrawn (discharged) from storage (MW)

- (Given) Forecasts:

$P_{RES,t}$	Sum of power production from renewable energy supply (MW)
D_t	Power level demanded from the loads at time t (MW)

- Decision and logical variables:

$P_{g,t}$	Power generated by DG unit in period t (MW)
$y_{g,t}$	Binary indicating if a unit g is on in period t
$E_{s,t}$	Energy stored in energy storage system s at the end of period t (MW)
$P_{s,t}$	Power output from storage unit s in period t (MW)
$P^{\mathrm{c}}{}_{s,t}$	Power charged to the storage unit s in period t
$P^{\mathrm{d}}{}_{s,t}$	Power discharged by the storage unit s in period t
n_s	Number of storage unit s in period t

3.3 Mathematical Model

Objective Function

The objective function for the cost model without storage represents the optimized operation of distributed generation units (g). In this regards, the optimized operation considers the minimized generation cost of all generation units (g) as described by their quadratic cost rate curves.

The objective function is presented in Equation (1).

$$J \coloneqq \sum_t \sum_g y_{g,t} * \left(A_g * {P_{g,t}}^2 + B_g * P_{g,t} + C_g\right) \tag{1}$$

Equation (1) describes the cost of the distributed generation units as a quadratic generation cost function associated with the fuel inputs and quadratic heat rate curves during each time increment (t). In our case the time increments over a one day period constitute to one hour. $y_{g,t}$ is a binary variable that indicates if a distributed generation unit (g) is generating power in period (t). Renewable generation is not included in the objective function but included as negative loads in the constraint equations due to the fact that they are assumed to be fully dispatched with zero marginal costs.

For the modification with storage, our study only concerns about the optimal usage of a fixed capacity of storage devices (e.g. PHEVs) which are fully controllable with no marginal fixed and variable costs when there power is needed. Therefore, the same objective function as developed in Equation (1) is used for both the standalone microgrid cost model with and without storage.

Constraint Equations

Besides the objective function, constraint equations are needed to reflect the technical and system constraints on generator operations. As the loads must be met at all times in a power system, Equation (2) requires the model to have sufficient generation available to balance demand and supply. As mentioned before, Equation (2) also makes sure that renewable energy generation is fully dispatched and treated as a negative load in the constraint equation.

$$\sum_{\boldsymbol{g}} P_{g,t} = D_t - P_{R,t} \quad \forall t \tag{2}$$

In addition, there also are minimum and maximum power levels for the generation units applied to the power output $P_{g,t}$ which are presented in Equation (3).

$$y_{g,t} * P_{g\ min} \leq P_{g,t} \leq y_{g,t} * P_{g\ max} \quad \forall g, t \tag{3}$$

Equation (3) represents real system constraints for the used equipment of distributed generation technology to generate power only within the range of minimum and maximum operating levels. The maximum and minimum power levels can be found from the technical performance data presented in Chapter 3.2.

Storage-specific Constraints

Although the implementation of a discrete storage systems does not modify the objective function in our mathematical model, it adds storage specific constraints to describe the characteristics of the storage devices. With reference to Chen et al. [CGW12], an additional charge and discharge equation need to be considered when storage is considered. The charge and discharge equation is represented in Equation (4).

$$E_{s,t+1} = E_{s,t} - \frac{P^{\mathrm{d}}{}_{s,t}}{\eta_d} + P^{c}{}_{s,t} * \eta_c \quad \forall s, t \tag{4}$$

Equation (4) includes all decision variables that are necessary to define the discrete storage dynamics in the time domain. In this regards, $P^{\mathrm{d}}{}_{s,t}$ is the power discharged by the battery bank during the time period t, $P^{\mathrm{c}}{}_{s,t}$ is the power charged by the grid to the battery bank, and $E_{s,t}$ is the energy stored in the battery bank at time t. η_d and η_c are respectively the battery discharge and charge efficiencies. Besides the storage dynamics, the storage units also needs to satisfy Equations (5) to (9).

To express the charged and discharged power of a storage unit as a single equation, Equation (5) defines the total power output $P_{s,t}$ of a storage system as the difference of $P^{\mathrm{d}}{}_{s,t}$ and $P^{\mathrm{c}}{}_{s,t}$ while considering charged inputs with a minus sign.

$$\sum_{\boldsymbol{s}} P^{\mathrm{d}}{}_{s,t} - P^{\mathrm{c}}{}_{s,t} = \sum_{\boldsymbol{s}} P_{s,t} \quad \forall t \tag{5}$$

Equation (5) helps to describe the charging and discharging behavior of a storage unit during time period (t) only as the power output $P_{s,t}$ of a storage system (s). As represented by Equation (6), this implication is useful to modify the power balance constraint after storage is included. [Liu10]

$$\sum_{\boldsymbol{g}} P_{g,t} + \sum_{\boldsymbol{s}} P_{s,t} \geq D_t - P_{RES,t} \quad \forall t \tag{6}$$

As for distributed generation units, storage units are also constraint by power limits (charging rates) and storage limits (battery sizes). Equation (7.1) and (7.2), includes storage-specific operational constraints for the minimum and maximum charging and discharging power levels of a storage unit besides the once that were already set up for distributed generation units in Equation (4).

$$0 \leq P^{\mathrm{d}}{}_{s,t} \leq n_s * P^{\mathrm{d}}{}_{s\,\max} \quad \forall s,t \qquad (7.1)$$

$$0 \leq P^{\mathrm{c}}{}_{s,t} \leq n_s * P^{\mathrm{c}}{}_{s\,\max} \quad \forall s,t \qquad (7.2)$$

In Equation (7.1) and (7.2), $P^{\mathrm{d}}{}_{s\,\max}$ and $P^{\mathrm{c}}{}_{s\,\max}$ are the maximum discharge and charge limit for an individual storage unit respectively. n_s is a parameter for the number of storage units that restricts the upper limit for a type of storage unit (s) used. Besides the power limits for charge and discharge, storage units are also constraint in there storage abilities. The limits for the minimum $E_{s\,min}$ and maximum storage $E_{s\,max}$ are shown in Equation (8).

$$n_s * E_{s\,min} \leq E_{s,t} \leq n_s * E_{s\,max} \qquad \forall s,t \qquad (8)$$

Finally, a terminal equality constraint that requires the starting E_0 and E_T ending limits of the storage in the battery to be equal is set up in Equation (9). Referring to Chen et al., the terminal equality constraint makes sure that the storage discharged will be fully returned by the end of the single day period and ensures that energy storage is not modelled limitless. [CGW12]

$$E_0 = E_T \qquad (9)$$

3.4 Model Data from the Mueller Community

Since 2011, a number of data sets have been publicly released that allow researchers among them the Pecan Street Research Institute Sample Data Set. [Bat14] The public data set was mainly released to enable the evaluation of smart metering technology and the design of the Mueller Community in Austin, Texas. The Mueller Community is a 711 acres microgrid demonstration project including smart grid systems for a group of single-family homes located at the former site of the Robert Mueller Municipal Airport approximately 3 miles from downtown Austin. At full build-out the community is supposed to include 4,900 single-family and multi-family dwelling units. [Rh14]

The microgrid aims to increase the energy efficiency of the community and operate as a test-bed facility for research and testing. The Mueller Community produces power from deploying a number of heterogeneous distributed generation units and electrical vehicles interconnected through a low voltage distribution system. The distributed generation technologies include roof-mounted photovoltaic (PV) systems, water heaters, and a gas-fired CHP combustion turbine. Further, the microgrid employs plug-in hybrid electrical vehicles to store and release power when needed.

Our results are presented for the residential load and PV generation data obtained for the Mueller community as of April 2015. During this time the Mueller Community consisted of the following components:

- **630 single-family homes including 256 houses equipped with roof-mounted PV systems;** with a total system size totaling to over 1.4 MW of installed solar power generation capacity at an average per-home system size of 5.5 kWh. Information about the solar panel characteristics are provided by [Rho14] [Eld11]. Hourly solar irradiation data from the National Renewable Energy Laboratory (NREL) of 2012 was used to estimate the aggregate generation of the PV systems.
- **A 4.6 MW Solar Turbines Centaur 50 gas-fired cogeneration plant fed by natural gas;** installed at Mueller and scaled for full build-out to cover the remaining load demand for periods of insufficient renewable energy generation. Information about the generation characteristics are provided in Stabler and Henderson [Sta04] [Hen02]. For the Austin installation, the plant is site rated including losses at 4.33 MW. [Sta04] Based on the data provided, we assume a similar heat rate curve in comparison to the Mercury 50 to model the generation cost curve for the Centaur 50 gas turbine as a quadratic function. [Hen02]
- **100 plug-in hybrid electric vehicles (PHEVs);** were subsidized for testing and research purposes in the Mueller community. Information about the PHEVs are shown in Table 1 and detail the operating constraints of a single electric vehicle as a single energy storage unit including charge and discharge rates, round-trip efficiency, marginal and installation costs, and total capacity.

Mueller Community Storage							
Source	**Type**	**Roundtrip Efficiency**	**Storage Size[1]**	**Max. Input[2]**	**Max. Output[2]**	**Fixed Cost[3]**	**Marginal Cost[3]**
PHEVs [HMW12]	ESS	0.9	0.0116	0.01	0.01	0.0	0.0

[1] in MWh [2] in MW [3] in $/MWh

Table 1. Mueller Community storage

Herein, PHEVs are treated as zero cost storage assuming that customers receive no benefits from the microgrid for the use of their storage devices. Also, PHEVs are assumed to be always available for microgrid storage and controllable as fully dispatchable storage source whenever their stored electricity is needed. [HMW12] As a result, we model the PHEVs included in Mueller similar to a normal storage devices as introduced by Chen et al. [CGW12]

1. Microgrid Load

Figure 7 shows the aggregated load profile for the 630 homes included in the Mueller community for summer and winter days. For average summer days, the aggregated daily load accounts to 16.11 MWh with peak power demand of approximately 1.05 MW for the time around 18 h. During night times, loads sharply drop and reach the minimum power demand of around 0.38 MW at 5 h in the morning. For winter days, the load demand is more stable and varies within the range of 0.25 - 0.52 MWh during the day. During winter, the aggregated daily load of 8.73 MWh accounts to approximately half of a summer day. Peak power demand in the winter similar occurs during evening hours. In the winter, power demand peaks at 19 h with peak power demand of approximately 0.52 MW. During night times, load steadily drops to minimum power demand of around 0.25 MW for the time around 2 h and starts to increase again after the 5h.

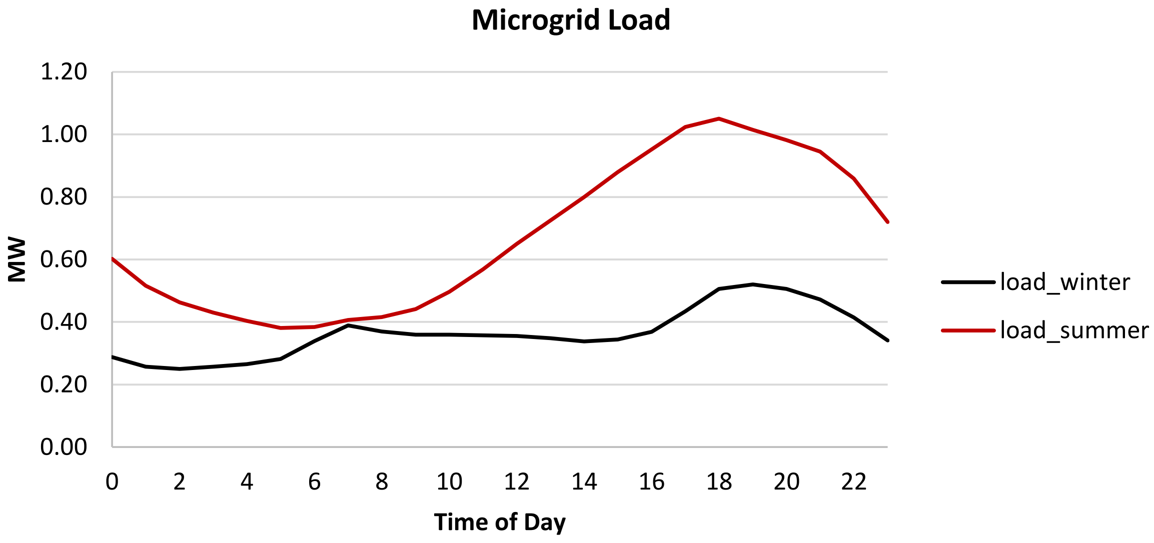

Figure 7. Total microgrid load during summer and winter (in MW)

2. PV Generation

As for microgrid loads, Figure 8 shows the aggregated PV power output from the 256 roof-mounted PV arrays for summer and winter days. Power from PV is limited and only available during a certain period of time throughout the day. Although the individual PV generation is intermittent and uncorrelated, at the aggregate level, the total generation follows a predictable smooth envelope for both summer and winter days. For summer days, the aggregated daily load accounts to 8.71 MWh with maximum power output of approximately 1.07 MW during noon-time hours. The power output is limited to the time of sunlight within the range from 6 – 19 h, and zero for times when no sunlight is available. Winter days decreases the quantity of PV power generated and shorten the time of available sunlight hours to 8 – 17 h. For winter days, the aggregated power output of 3.71 MWh accounts to less than half of a summer day with a maximum power output of approximately 0.52 MW for the time around noon.

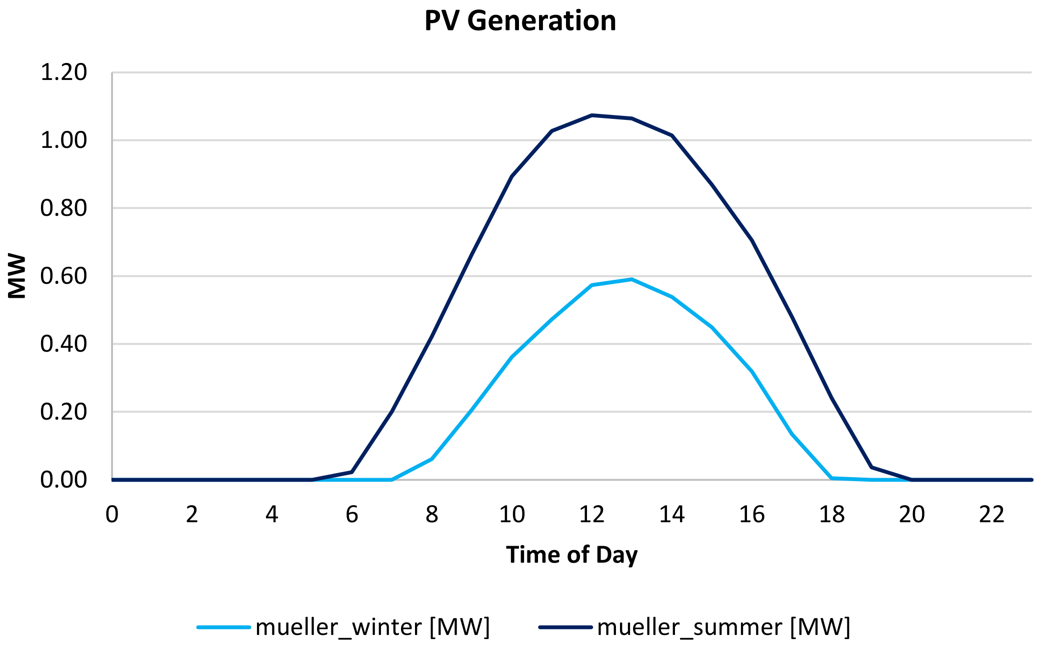

Figure 8. Aggregate PV Generation by summer and winter days

3. Net Renewable Electricity Usage and Storage Potential

To minimize generation costs and meet load demand, renewable energy is used as much as possible during times when renewable energy sources are available. Figure 9 illustrates the net renewable electricity usage in the Mueller Community by comparing the total demand from the residential loads with the potential PV generation during both summer and winter days. As we can see, the potential amount of PV generation is not enough to fully supply the daily load but may exceed the load during noon time periods with heavy sunlight hours. Figure 9 also shows the excess power from PV by the shaded area that is lost without storage. In the storage case, negative net electricity usage can be saved depending on the size of the storage and used in future periods to reduce the cost from distributed generation. Hence, excess power from solar generation is lost in the shaded area when PHEVs aren't controlled as energy storage devices in the Mueller Community.

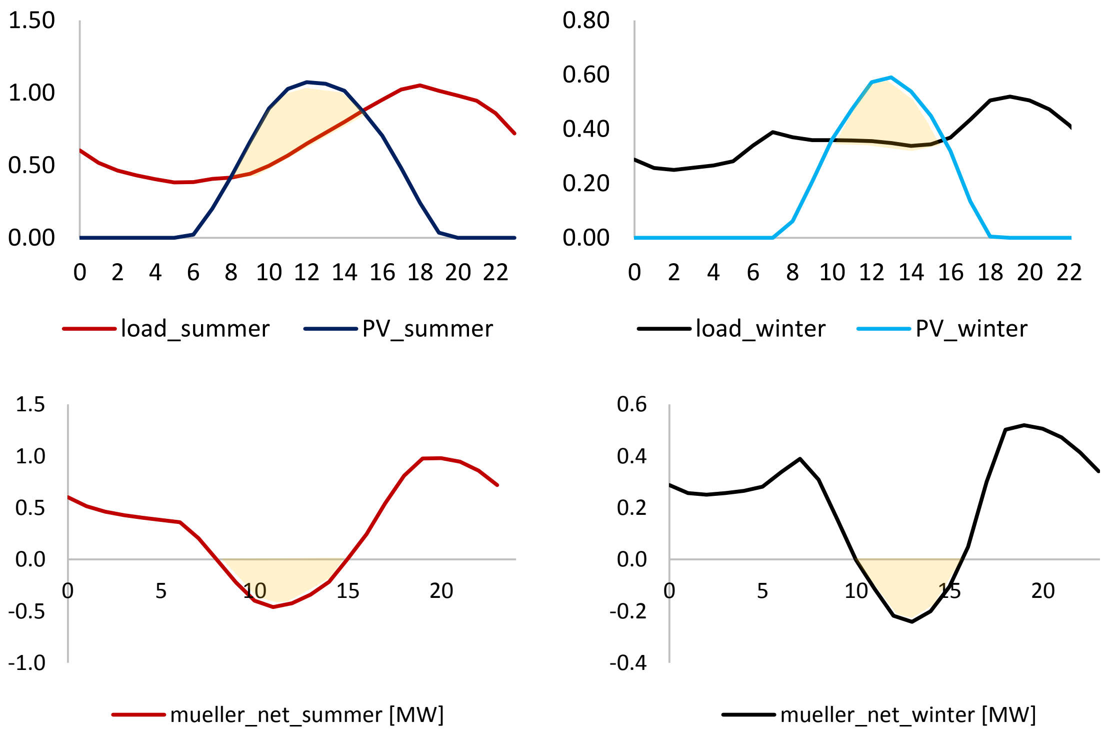

Figure 9. Net renewable electricity usage for the Mueller Community (by season) [in MW]

3.5 Generation Cost Analysis for the Standalone Operation of Mueller

Based on the data described, the results are presented for the residential load and PV generation data obtained for the Mueller community including 630 homes, 100 PHEVs and 256 roof-mounted PV systems with an average per-home system size of 5.5 kWh. We recall that the Mueller Community generates power only from one single 4.33 MW gas turbine with generation costs following a quadratic cost rate curve. Thus, for time periods when PV is insufficient to cover the power demanded by the consumers, the gas turbine is turned on as a load balancing generator to generate the power shortage. Obviously, in the case of a single gas turbine the unit commitment problem reduces to a cost calculation problem for the generation cost of the microgrid. In this respect, the DG output is calculated as the difference of the microgrid load and the PV generation in each time period where PV is insufficient to fully supply the loads.

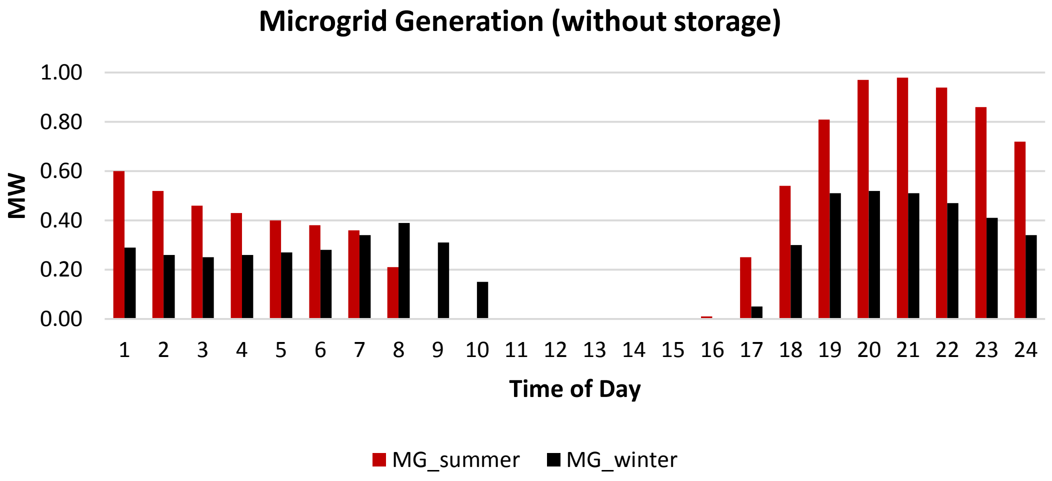

Figure 10. Microgrid generation without storage for summer and winter days (in MW)

As a result, the answer to the standalone optimization problem for the Mueller Community is straight forward. After PV is used as much as possible to meet the demand, the optimization problem reduces to a cost calculation problem for the generation output of the microturbine. The microgrid generation cost for covering the remaining demand is then calculated by using the quadratic cost function for each hourly output and summed up over a 24 hours of a single day period. The generation output for summer and winter days is shown in Figure 10 respectively. In this case, the summer daily generation cost sums up to $633.25 with a total generation output of 9.46 MWh and maximum generation output of 0.98 MW at 21 h. For winter days, the daily generation cost accounts to $585.35 with a total generation output of 5.90 MWh and maximum generation output of 0.52 MW at 20 h.

As already mentioned before, the motivation to utilize available PHEVs as storage stems from the fact that energy storage systems allow to store the excess power generated from renewables. For the Mueller microgrid, a number of 100 PHEVs restricts the community storage to reach optimality. Recall that in our case study PHEV customers receive no benefits from the microgrid for the use of their storage devices, and allow their cars to be always fully available for microgrid storage whenever their storage capacity is needed.

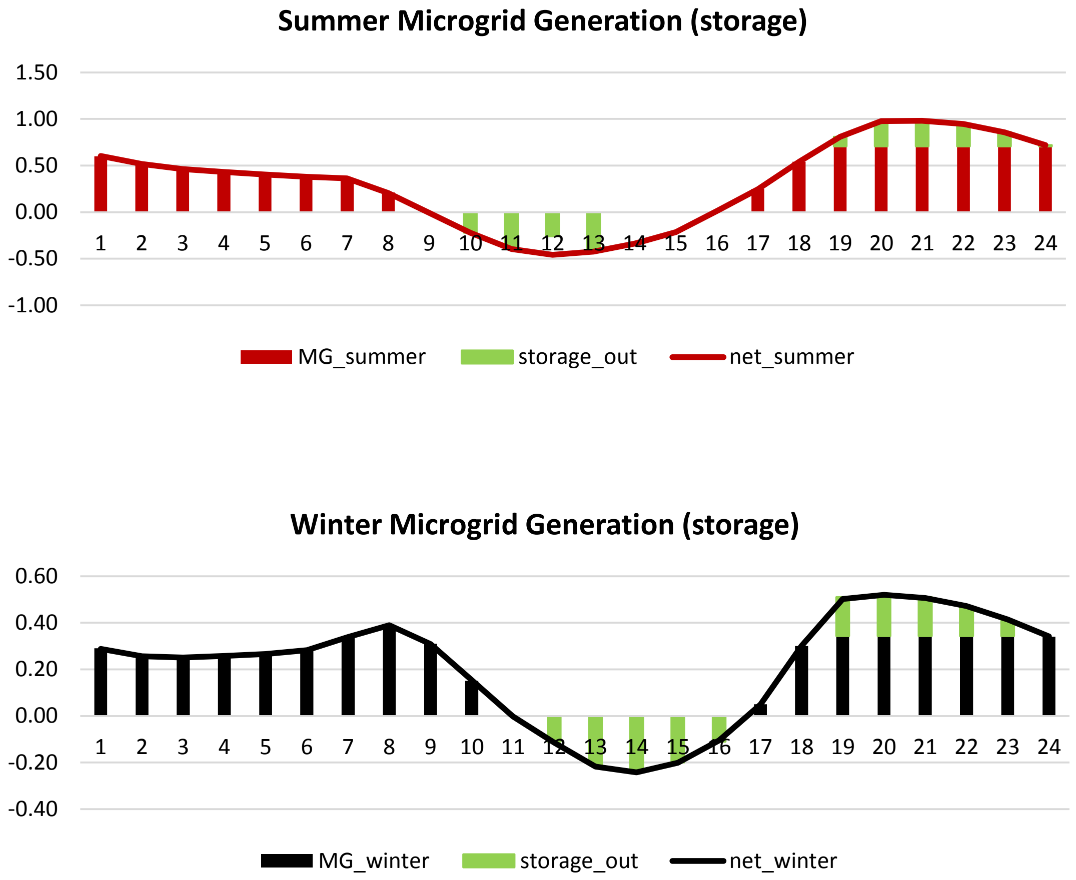

Figure 11. Microturbine generation with storage during summer and winter days (in MW)

Figure 11 shows the microturbine output for the Mueller community during summer and winter days when PHEVs are considered as controlled storage devices by the microgrid. In comparison to the case with no storage (s. Figure 10), we find that the microturbine output reduces during hours of peak demand for both scenarios resulting in a total generation output of 8.40 MWh during summer and 5.21 MWh during winter days. The reduction in total generation output results from utilizing PHEV storage during times of high penetration of PV.

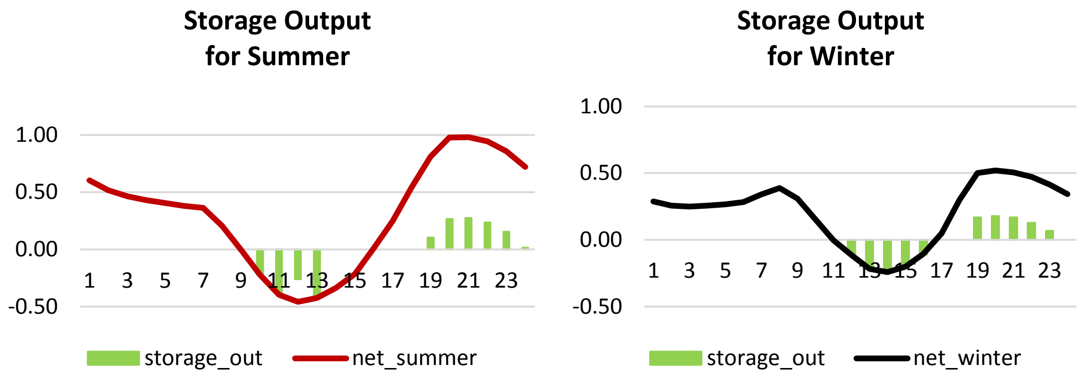

Figure 12. Storage output during summer and winter days (in MW)

As expected, Figure 12 clearly shows that power is charge to the battery during times of high renewable energy penetration and discharged during times of peak demand. During summer, an aggregated amount of 1.29 MWh is charged for the high sunlight period from 10 - 13 h and discharged during peak evening hours. We see that in the summer case, the size of available PHEVs in Mueller is not large enough to store the total amount of 2.1 MWh of excess solar power during summer times. As the excess of solar power during winter times is only 0.87 MWh, the total amount can be charged to the battery during hours of sunlight accounts for the period from 12 - 16 h. In this respect, our findings for storage during winter and summer periods are coherent with the solar irradiation profiles as shown in Figure 8.

In the case of storage, the daily generation cost for summer reduces to $611.25 with a reduced generation output of 1.04 MWh by utilizing the whole fleet of 100 PHEVs. For winter days, the daily generation cost reduces to $571.06 with a reduction in generation output of 0.7 MWh by utilizing 68 PHEVs.

Chapter 4

Evaluation of Utility Generation Costs from Standalone Operation

In the following, we introduce a cost model for the utility to calculate the “as-if” standalone generation costs when there is no power exchange with the microgrid in an interconnected power system. For the utility’s generation cost, we use an aggregated generation unit obtained through dispatching all available thermal units to construct its short-term generation cost function.

4.1 Introduction

In power systems analysis, decision models are important for the management and scheduling of power generation. Generally, they combine economic dispatch (ED) and unit commitment (UC) to determine the operating generators and output levels for each time period in the modeled system. In this regards, economic dispatch minimizes the operational costs by allocating the optimal amount of power to a given set of available generators at each time step. [MuK77] Unit commitment, on the other hand, decides when to commit an individual generator for power dispatch while taking into consideration specific system and generation constraints. [Bal95] Different solution techniques are found in literature to solve the unit commitment problem [Pad04].

In comparison to microgrids, unit commitment models for utility networks usually concern about much larger numbers of generators and system constraints. To reduce the problem complexity and computational requirements typically methods such as Lagrange multipliers or Lagrangian relaxation are used in utility models. [Fis04] In order to reduce the problem sizes for utility networks with a large number of generation units, aggregation is an efficient method to correctly value the marginal costs for unit commitment problems with dynamic constraints. [LAB11]

4.2 Problem Formulation

To model the utility, we assume a purely thermal power system that is decoupled from the microgrid. Similar to the model developed by Chang et al. we use an aggregated generating unit obtained through dispatching available thermal units by the lambda iteration method to construct the utility's thermal cost function based on the minimization of generation cost. [CCL90] In other words, we define the generation costs and constraints of each generation unit as a function of the level of aggregate unit output and aggregate all available thermal units into one equivalent unit to construct the generation cost function. Also, we assume that under the system operation conditions short-term commitment changes are not allowed for most of the base- and medium-load thermal units. Hence, we reduce the scheduling of the hourly thermal generation over a one-day period to an economic dispatch problem. [CCL90] To aggregate the utility into one equivalent unit, we introduce some notations for the aggregate unit similar to the methods proposed by Langrene et al. [LAB11] More details on the formal definition of an the aggregated unit can be found in Hargreaves and Hobbs. [HaH12]

Standalone utility cost model with storage

- Index/sets:

u	Set of all generating units within an aggregate unit
t	Time periods in 1-hour increments

- Parameters:

- Cost function

J ( ) Utility generation cost function

A_u	Constant from generation cost curve for aggregated utility unit u
B_u	First order component of generation cost curve for aggregated utility unit u
C_u	Second order component of generation cost curve for aggregated utility unit u

- Power limits

$P_{u\,min}$	Minimum aggregated power level of the utility (MW)
$P_{u\,max}$	Maximum aggregated power level the of utility (MW)

- (Given) Forecasts:

D_t	Power level demanded from the utility loads at time t (MW)

- Decision and logical variables:

$P_{u,t}$	Power generated by aggregated utility unit in period t (MW)

4.3 Mathematical Model

To obtain the utility cost function that minimizes generation costs, we aggregate all the available thermal units of the utility network into one equivalent aggregate thermal unit. The ideal definition of an aggregate unit will meet some objective across all levels of output of an aggregate unit. [HaH12]. Therefore, we perform unit commitment and economic dispatch over the set of all available thermal units to find the minimized generation cost for each given load level. Next, we derive the aggregated thermal unit by fitting a cost function to the data points of generation cost at each load level. The thermal cost function is approximated by a second order polynomial.

The aggregate thermal cost function for the Taipower Company is shown in Table 2.

Scheduling Horizon (in h)	No. of Plants	Cost Function of the Aggregated Thermal Unit (in $)[1]
24	3	$0.0025 * P^2 - 8{,}95 * P + 41077$
24	7	$0.0024 * P^2 - 5.20 * P + 23519$
24	***10 (W)***	$\mathbf{0.0021 * P^2 - 7.84 * P + 78526}$
24	***10 (S)***	$\mathbf{0.00235 * P^2 - 12.08 * P + 94142}$
72	10	$0.0021 * P^2 - 7.84 * P + 78526$
168	10 (W)	$0.0021 * P^2 - 7.84 * P + 78526$
168	10 (S)	$0.00235 * P^2 - 12.08 * P + 94142$

[1] USD to TWD = 31$

Table 2. Aggregated Thermal Unit of the Taipower Company (in $) [SCC90]

Relevant cost functions were generated based on different model periods and numbers of thermal generation units. Generation specific information on the thermal generating fleet was provided by Taipower Company. For our studies, we use the cost functions obtained for a scheduling period of 24 hours during both summer and winter days. In this regards, we assume that the cost functions for a period of 24 hours equal the cost function of 168 hours.

4.4 Model Data from the Taiwan Power Company

The electric power system in Taiwan is mainly operated by Taiwan Power Company. Taiwan Power Company is a vertically integrated, practically fully state-owned power utility company. Its business scope includes generation, transmission, distribution and sales. After the liberalization of Taiwan’s electricity market, Taipower established effective power purchase agreements with independent power producers (IPPs) to diversify its generation portfolio, and reduce its overall generation and investment costs. In the transmission sector, Taipower still enjoys monopoly power and owns almost all transmission and distribution lines in Taiwan. [Wan06]

Microgrid systems are important for power systems in areas that lack conventional energy resources but have a high potential of renewable energies reserved. Taiwan is a densely populated island with limited natural resources which can only meet around

3% of its energy needs from indigenous fuel resources and heavily relies on energy imports. [Wan06] Consequently, the increasing energy consumption and the difficulty of power plant construction on the densely populated island puts considerable pressures on Taiwan’s electricity system. However, Taiwan has a high potential renewable energy reserves as measured in kWh per day per person (kWh/d/p). According to the estimation of Chen et al., wind and solar energy have the highest renewable energy potential in Taiwan [Che10].

Consequently, microgrid networks that promote the deployment of small scale distributed energy resources e.g. solar and wind, and effectively utilize renewable energy resources can help Taiwan to increase their energy efficiency, independency, and security. This motivated us to choose Taiwan as the test-location in our studies and suggest the interconnection for the joint operation between the Taiwan Power Company (TPC) and the Mueller microgrid as introduced in Section 3.1. Data about the Taipower loads and generating fleet has been provided by Chang et al. [CCL90]

1. Utility Load

Figure 13 shows the load profile of the Taipower Company for summer and winter days. [CCL90] For the summer scenario, the aggregated daily load accounts to 202,450 MWh with peak power demands of approximately 10300 MW at 12 h and 16 h. During night times, load steadily drops to a minimum of 6000 MW at 5 h in the morning. The load shape in winter looks quite similar but with lower load levels for each time period. During winter, the aggregated daily load of 159,750 MWh accounts to approximately 79% of the summer scenario. Peak power demand in winter occurs at 11 h and 18 h with load levels of about 8200 MW. After reaching the evening peak load, the load steadily drops to a minimum of 4650 MW at 2 h and increases again afterwards.

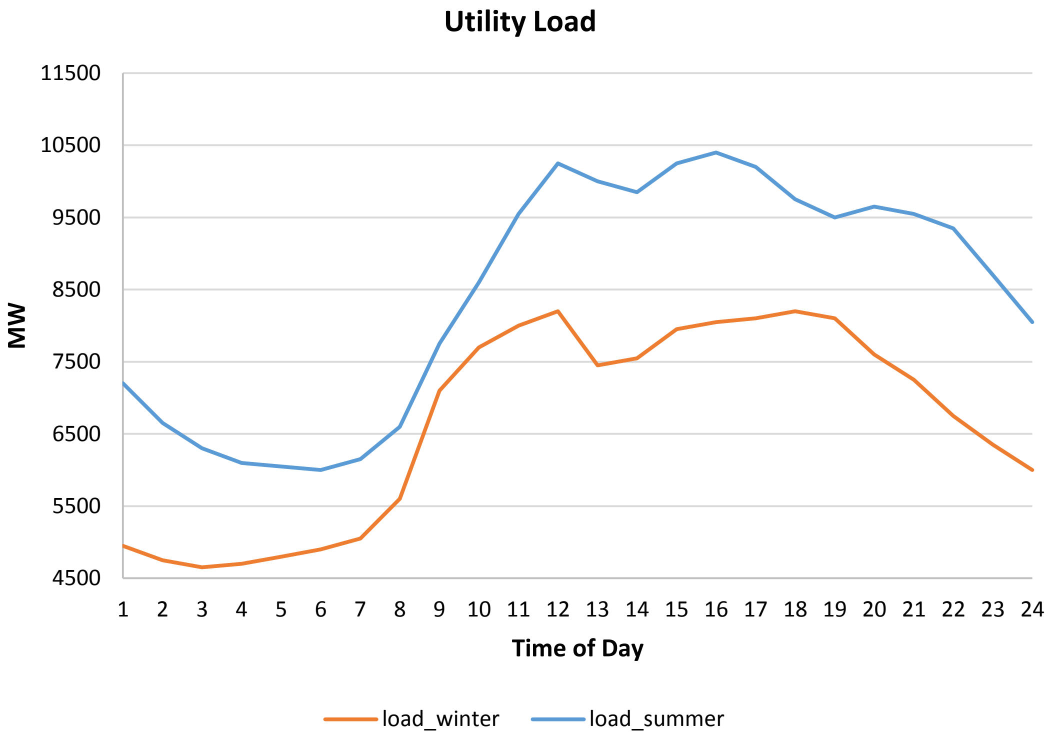

Figure 13. Utility load by summer and winter season [SCC90]

4.5 Generation Cost Analysis for the Standalone Operation of Taipower Company

To evaluate the cost sharing benefits from joint generation and storage between the Mueller Community and the Taiwan Power Company, we first calculate the minimized generation cost for the utility production of Taipower Company. Therefore, we calculate the hourly generation costs based on the aggregated utility cost functions in Table 2 for supplying each load level and sum up the daily generation cost for summer and winter days respectively. The aggregated power generated by available thermal generation units for each time interval is shown in Figure 14.

For the daily load profile, the minimized daily generation cost for Taipower is \$3,979,560 in summer and \$2,917,926 in winter. In summer, the hourly generation cost ranges from \$106,432.94 to \$223,202.58 per hour. For the winter scenario, costs are lower and range between \$86,730.94 and \$153,093.03 per hour.

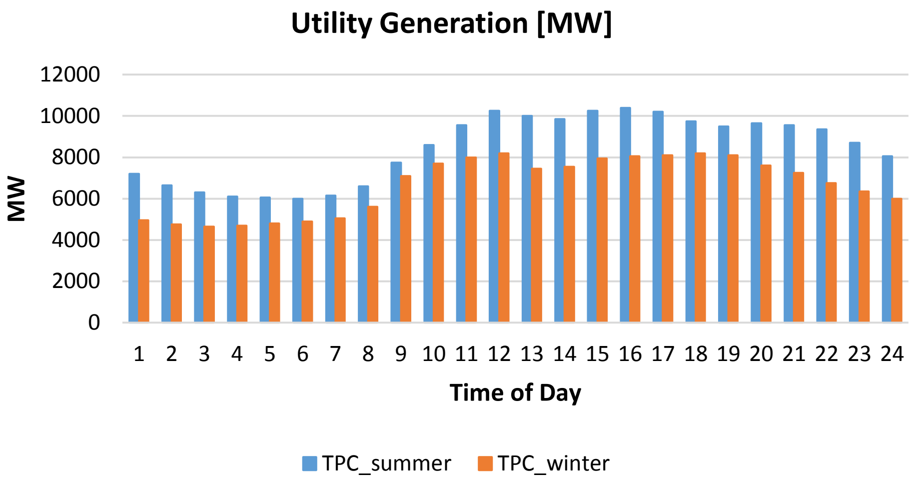

Figure 14. Aggregated thermal generation for summer and winter days (in MW)

Chapter 5

Evaluation of Generation Costs for the Joint Operation of Microgrids and Utilities

To compensate for power exchange on the basis of fairly allocated joint generation costs, we need to compare the "as-if" standalone generation costs for both the microgrid as defined in Chapter 3 and the utility grid as defined in Chapter 4 with their joint operation cost under power exchange. Therefore, in the following, we develop a cost model which cooperatively minimizes short-term operation costs. In this thesis, it is the task of a centralized market coordinator with complete information about the individual cost curves to jointly dispatch available generation units and adduce an aggregated load schedule. As discussed before, the central dispatch between the microgrid and the utility is only through their daily generation cost.

5.1 Introduction

Two market policies are assumed for the joint operation of a microgrid and its hosting utility. [Hat05] In the first policy, the microgrid aims to self-sufficiently satisfy its local energy demand without exporting power to the upstream distribution grid, and concerns about minimizing the operational costs of internal production and imported energy from the utility grid. As termed in Schwaegerl et al., this is equivalent to the "good citizen" model. [Sch08] In the second policy, the microgrid can sell and buy power to the grid via an aggregator or energy service provider (ESP) and is allowed to participate in the open market via energy trading with the extant grid Schwaegerl et al. describes this case as an "ideal" citizen model. [Sch08]

Initially, the problem of joint dispatch has been introduced for vertically integrated utilities in regulated markets to cooperatively gain and share the benefits through economies of scale and making the best use of all available resources. To address the problem, utilities traditionally formed coalitions, e.g. in the form of power pools, to jointly dispatch their generation resources and thereby achieve cost savings from optimal usage of transmission facilities [YuD96] [TaL02] or emission trading [Cha95]. Particularly against the background of the benefits that arise from energy transactions between a microgrid and its extant power system, this is also an issue for the energy exchange and joint operation of a microgrid and its hosting utility.

In this regards, Asimakopoulou et al. suggests a decision framework for cooperatively optimizing the energy management of a large central production unit and an energy services provider (ESP) representing several microgrids. [Asi13] His paper serves as a benchmark in an attempt to highlight the differences between a decentralized and centralized decision model for their joint operation as summarized in Table 3.

	Decentralized Decision Model	**Centralized Decision Model**
Method	Interaction between ESP and upper level production unit modeled as a bi-level programming problem	Interaction between ESP and upper level production unit modeled as a single objective maximization problem
Motivation	Interdependent decision making between the upper and lower level	Global decision making for upper and lower level managed as a single entity
Objective	The upper level production unit decides upon a profit margin taking into account the energy needs of the ESP to the market prices.	Since there is only one entity, the objective is the maximization of total profit acquired by adducing a joint generation without a profit margin of the utility.

Table 3. Decision models for the interaction between the utility and the microgrid

5.2 Problem Formulation

To develop a joint generation cost model for the energy exchange between a microgrid and its hosting utility, it will be assumed that the utility and the microgrid each with their own generation and loads are operating as an interconnected power system where generation is centrally dispatched. In this regards, a centralized market coordinator with complete information regarding the cost functions of all generation units is assumed. Based on this information, its responsibility is to independently dispatch all available generation resources and minimize the joint generation cost from delivering an aggregate load schedule. As mentioned before, since there is only one single entity the objective is to minimize daily joint generation costs in an idealistic way by adducing a joint load schedule without a profit margin of the utility.

The decision model is inserted into the overall architecture of a single microgrid and a utility grid with fixed installed capacities. Parameters and input variables are deterministic. They consider the electrical load profiles, microgrid and utility generation constraints, ambient conditions and economic generation data. Thus, with the purpose of cost sharing, the optimization problem comprises the fuel cost of DG, the generation cost of the utility grid, and the energy exchange between the individual systems. Finally, the decision variables and the governing equations are defined.

- Index/sets:

g	DG generating units
k	Utility generating units
t	Time periods in 1-hour increments

- Parameters:

- Cost functions

$\boldsymbol{J_M}$ ( ) **MG generation cost function**

A_g	Constant from generation cost curve for DG unit g
B_g	First order component of generation cost curve for DG unit g
C_g	Second order component of generation cost curve for DG unit g

$\boldsymbol{J_U}$ ( ) **Utility generation cost function**

A_u	Constant from generation cost curve for aggregated utility unit u
B_u	First order component of generation cost curve for aggregated utility unit u
C_u	Second order component of generation cost curve for aggregated utility unit u

- Power limits

$P_{g\,min}$	Minimum power level of DG unit g (MW)
$P_{g\,max}$	Maximum power level of DG unit g (MW)
$P_{u\,min}$	Minimum aggregated power level of the aggregated utility unit u (MW)
$P_{u\,max}$	Maximum aggregated power level the of aggregated utility unit u (MW)

- (Given) Forecasts:

$P_{R,t}$	Sum of power production from renewable energy supply (MW)
$D_{MG,t}$	Power level demanded from the microgrid loads at time t
$D_{U,t}$	Power level demanded from the utility loads at time t

- Decision and logical variables:

$P_{g,t}$	Power generated by DG unit g in period t (MW)
$P_{u,t}$	Power generated by aggregated utility unit in period t (MW)
$y_{g,t}$	Binary indicating if a unit g is on in period t

5.3 Mathematical Model

Objective Function

The objective function of the centralized problem minimizes the joint generation cost of a single entity considering both the utility and microgrid generation cost model as developed in Chapter 3 and 4. In this case, the joint decision problem optimizes the production of a fixed capacity of microgrid and utility generation units. Referring to the notations introduced before, the joint generation cost can thus be expressed as an aggregate function of utility and microgrid generation output.

Our objective is to find a joint generation schedule that minimizes daily operation costs while meeting the aggregated load and both system constraints. The objective function of the joint generation cost model is presented in Equation (1).

$$\min_{\substack{P_{g,t}\\ P_{u,t}}} \sum_{\boldsymbol{t\in T}} \sum_{i \in G} y_{g,t} * \left(A_g * {P_{g,t}}^2 + B_g * P_{g,t} + C_g\right) + \sum_{t\in T} \left(A_u * {P_{u,t}}^2 + B_u * P_{u,t} + C_u\right) \quad (1)$$

The first term of Equation (1) captures the generation costs of the microgrid distributed generation units (g) associated with their quadratic cost rate curves during each time period (t) over the model period. The second term represents the utility generation cost as one equivalent thermal unit aggregating all available utility generation units into one single cost function. [CCL90]

Constraint Equations

The technical and system constrains for joint generation scheduling are presented for both models. As the loads of both system must be balanced, Equation (2) requires sufficient power generation to fully adduce a joint schedule during all time periods. Due to the fact that renewable generation is assumed to be fully dispatched with zero marginal costs they are included as deterministic negative loads.

$$\sum_{\boldsymbol{g}} P_{g,t} + P_{u,t} = D_{MG,t} + D_{U,t} - P_{R,t} \quad \forall t \tag{2}$$

In addition to the power balance constraints, Equation (3.1) and (3.2) includes minimum and maximum power levels for the distributed and utility generation units applied to the power outputs $P_{g,t}$ and $P_{u,t}$ respectively.

$$y_{g,t} * P_{g\ min} \leq P_{g,t} \leq y_{g,t} * P_{g\ max} \quad \forall g, t \tag{3.1}$$

$$P_{u\ min} \leq P_{u,t} \leq P_{u\ max} \quad \forall t \tag{3.2}$$

After including storage, storage specific constraints are additionally considered as presented in Section 3.3.

5.4 Generation Cost Analysis for the Joint Generation between the Mueller Community and the Taipower Company

As described in the previous sections, we develop hypothesis for the load and renewable generation profiles of the Mueller microgrid and the Taipower Company utility network based on the data provided in Chapter 3 and 4. Parameter inputs are given for their fixed configurations and used in a deterministic scheduling problem to

i. suggest an interconnected power system that allows energy exchange and joint operation between the micro- and utility grids

ii. manage the power grids as single production entity ideally controlled by a centralized decision maker to cooperatively minimize daily generation costs

iii. calculate the reduced system generation costs from the power exchange coalition as a foundation for sharing the savings between the model grids through fair payments for energy exchange

The joint generation scheduling problem is to determine the optimal mix of utility and microgrid generation units based on the minimization of shared total costs after the total power output from PV is subtracted from the aggregated load schedule. To find an optimal generation schedule for the joint operation of Taipower and the Mueller microgrid, we manage them as a single generating entity under ideally centralized dispatch of a market coordinator with perfect information to jointly adduce the load schedule. Due to the variations in seasonal load profiles, we find different results for a summer and winter scenario. Note, in the following figures the primary vertical axis denotes the power output from Taipower and the secondary vertical axis the power output from the microgrid.

Joint Generation of Taipower Company and Mueller Community without storage

Figure 15 and Figure 16 show the cost-minimizing joint generation schedules when PHEVs aren’t controlled as storage devices for summer and winter respectively.

1. **Mueller microgrid generates at maximum capacity to avoid the commitment of expensive peak power plants in summer (Figure 15):** For peak demand levels in summer, the Mueller microgrid generates at maximum capacity from 10 h to 23 h to avoid the commitment of expensive peak load power plants by the utility. Therefore, we suggest an “ideal citizen” model with bidirectional flow of energy between the utility and the microgrid which reduces the costs from high levels of peak power demand during summer.

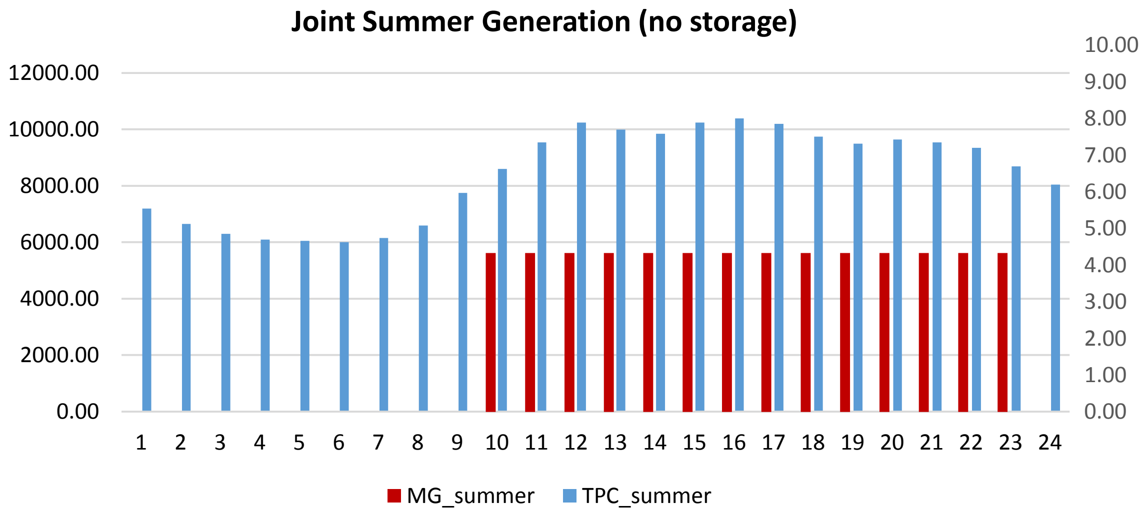

Figure 15. Joint generation without storage during summer days (in MW)

2. **Taipower generates the entire power for the interconnected system and exports necessary power to the microgrid during winter (Figure 16):** For lower peak demand levels with maximum loads below 8200 MW in winter, Taipower generates the entire power for the interconnected system due to strictly lower generation costs

over all load levels. In this case, a “good citizen” model with one directional power flow from the Taipower Company to the Mueller Community is sufficient for the mutual energy exchange between the systems. Accordingly, joint generation scheduling only concerns about the utility production and the exported energy from the utility grid to the microgrid as it is financially beneficial for the whole system.

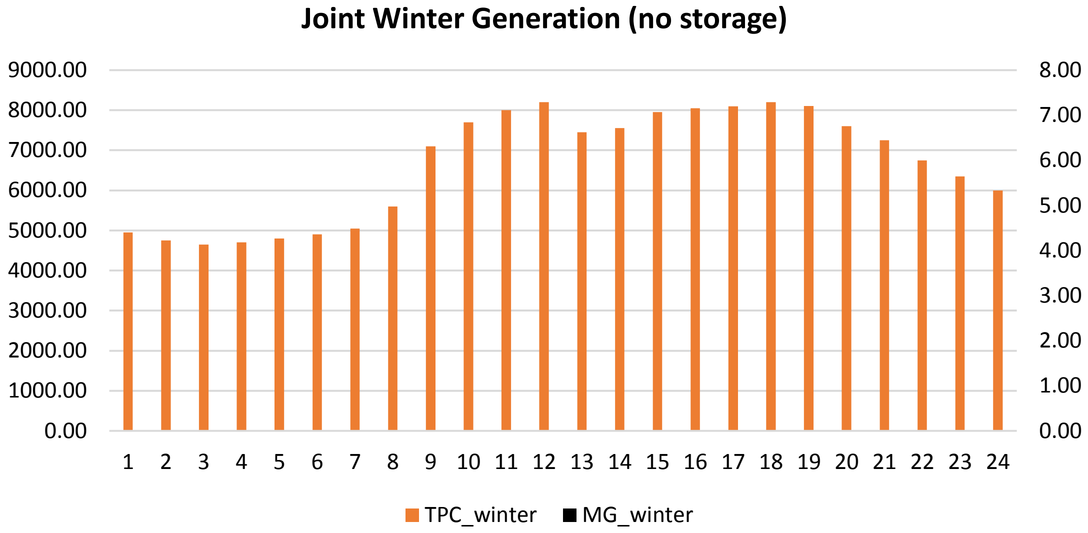

Figure 16. Joint generation without storage during winter days (in MW)

Joint Generation of Taipower Company and Mueller Community with storage

Figure 17 shows the joint generation output for the Taipower utility and the Mueller microgrid for both summer and winter days when PHEVs are controlled as storage devices.

3. **Unit commitment decisions don’t change with the control of PHEVs as storage devices (Figure 17):** The penetration of solar power and storage devices are infinitesimal small and have insignificant effects on the variation of total loads, and

therefore don’t change unit commitment decisions. As illustrated, Taipower continues to entirely supply the total demand during winter days and the Mueller microgrid helps to reduce high cost from peak power supply during the summer. Nevertheless, storage devices can help to reduce power generation during peak demand periods.

Figure 17. Joint generation with storage during summer and winter days (in MW)

4. **Storage devices are fully controlled to hedge against high generation costs during peak demand hours (Figure 18):** In comparison to the standalone microgrid case where cost savings arose from storing excess renewable energy, under joint generation saving benefits rather arise from the possibility to hedge against high generation costs to supply peak levels. Herein, storage helps to reduce the costs from varying load levels by charging power to the battery during times of low-cost demand periods and discharging power from the battery during times of peak demands with high generation costs.

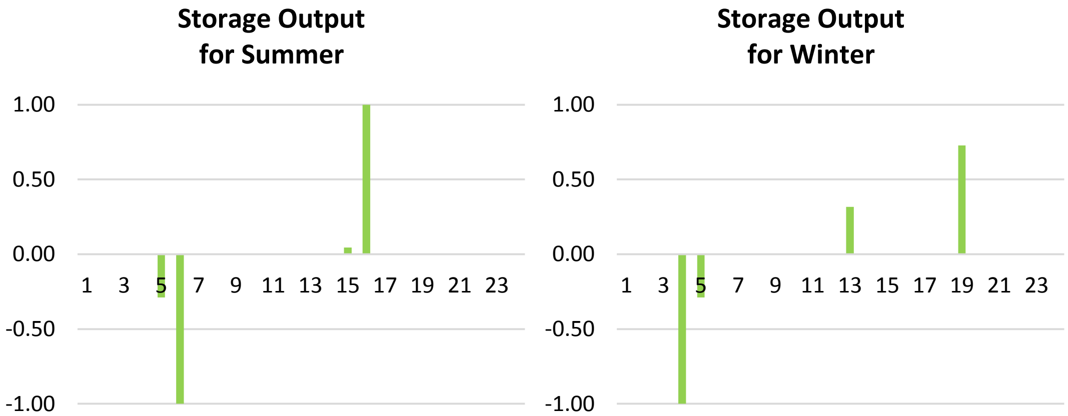

Figure 18. Storage output during summer and winter days (in MW)

In summary, the minimized daily generation cost without storage accounts to \$3,979,348 with a total generation output of 202,396.5 MWh in summer. During winter, the minimized daily generation cost is calculated only with respect to the generation cost function of the utility and sums up to \$2,918,013 with a total generation output of 159,775 MWh for the supplying the aggregated load schedule. In comparison to the joint generation model without storage, the daily generation cost reduces to \$3,979,330 in summer and to \$2,917,854 by utilizing a storage fleet of 100 PHEVs for both scenarios. A detailed discussion of possible generation scenarios and realized cost savings from joint operations between the model grids is provided in Section 6.3.

Chapter 6

Shapley Value Based Payment Calculation for the Energy Exchange between a Microgrid and the Utility

As we saw from our calculations in Chapter 3 to Chapter 5, joint operations of a microgrid and its hosting utility may lead to reduced operation cost by jointly delivering an aggregate load schedule through a cooperative decision model. To calculate the payments of power exchanged, however, a method which fairly accounts for individual cost and generation contributions to the joint operation is needed.

The Shapley value constitutes as such a method and helps us to compensate for energy exchange through fair payments for power transactions between the microgrid and the utility due to a mutually agreeable division of joint operation costs. Assuming that a coalition of players cooperates, it is “fair” in the sense that it compensates each player based on its marginal contribution to the overall gains from that coalition. Following this concept, the contribution of this chapter is to propose a Shapley value-based payment calculation scheme for the power transactions between the Mueller microgrid and the Taipower Company during a one-day period.

6.1 Introduction

In recent years, the theoretical analysis to develop criteria and methods for cost allocation problems emerged as the field of cost sharing games. [JaM07] To address a common cost allocation problem, several methods have been discussed for the distribution of joint cost and the division of surplus, among others the Shapley value [FrM99] The Shapley value was introduced by Shapley as a method for players to asses a priori their benefits from playing a game and suggested as a joint-cost allocation scheme in various fields of research. Today, the Shapley value is perhaps the most commonly used method to allocate the costs in cost sharing games as it is budget-balanced and guarantees equilibrium existence in any game, regardless of its parameters. [GMW11] In the power market environment, the application of the Shapley value mainly found its applications to fairly allocate transmission expansion or emission costs from vertically integrated utilities. [TaL02] [Cha95]

Its many applications and favorable properties motivate the development of a concept to calculate fair payments for mutual power transactions between a microgrid and its utility under cooperative energy exchange in joint operations.

6.2 Methodology

Cost sharing games provide a proper basis to allocate the costs for a group of parties that wants to divide the cost of a common facility or operation. In this regards, each party has a standalone cost if it does not cooperate with the others. Similarly, each subgroup of parties has a shared cost if parties cooperate with each other but not with the remaining parties. Even though cost sharing games allow to assess the value of a coalition in the context of a given scenario, they don't solve the problem how the value should be shared. Therefore, a cost sharing rule can help to allocate the total cost among the members of a group for every possible cost sharing game.

Among others, the Shapley value is a payoff allocation approach which assigns a fair distribution to the total surplus generated among all members of a coalition based on their marginal contribution to the overall gain of a coalition. The idea is that given a cost sharing game, players join the game one at a time in some predetermined order. As each player joins, a player's cost contribution is its net addition to the cost as it joins. The Shapley value of a player is its average cost contribution over all possible orderings of the players and supports a mutually agreeable division of costs with certain fairness properties. [Bre13] Its unique feature is that it is budget-balanced and guarantees equilibrium existence in any game regardless of its parameters. [GMW11]

Mathematically, the allocation φ_i to the player i can be expressed as

$$\varphi_i(v) = \sum_{S \subseteq N\{i\}} \frac{|S|!\,(n-|S|-1)!}{n!} \times [\, v(S \cup \{i\}) - v(S)\,] \qquad (1)$$

where S is the number of players in the coalition, N is the total number of players in the game, v is the characteristic function representing the total jointly earned payoff or benefit of a coalition S, and i is any player in the game. The term v(S ∪ {i}) − v(S) refers to the marginal contribution of player i to the value of the whole coalition v(S). Further, the expression $\frac{|S|!(n-|S|-1)!}{n!}$ depicts the weighting factor which allocates proportional share of marginal contribution of each player in the coalition. [Has14]

As a result, the Shapley value φ_i is assigned to a player i according to a given function v that determines the gain v(S) for a coalition game (N, v) with transferable utility for player set N measured by a function v for any non-empty subset S ⊆ N. The advantages of this method are that this approach is budget-balanced and guarantees equilibrium existence in any game regardless of its parameters. Also, it has some important properties that hold when allocating the cost in a cost sharing game [Bre13]:

1. **Pareto-efficiency:** The total value of a coalition is distributed among the members: $\sum_{\boldsymbol{i \in N}} \varphi_i(v) = v(N)$
2. **Symmetry:** The value can be determined regardless of the name of the players. If for any two players i and j the following holds: $v(S \cup \{i\}) = v(S \cup \{j\})$ for every subset S ⊆ N with $S \cap \{i,j\} = \emptyset$, then $\varphi_i(v) = \varphi_j(v)$.

3. **Additivity:** This property requires for any two games $\varphi_i(N, \upsilon)$, $\varphi_i(N, \upsilon^*)$ that: $\varphi_i(N, \upsilon) + \varphi_i(N, \upsilon^*) = \varphi_i(N, \upsilon + \upsilon^*)\ \forall i\ \in N$

4. **Zero player:** If the marginal value of a player to any possible coalition is zero, this player gains a value of zero: $\upsilon(S \cup \{i\}) = \upsilon(S)\ \forall S\ \Rightarrow\ \varphi_i(\upsilon) = 0$

6.3 Shapley Value Payment Calculations for the Energy Exchange between the Taipower Company and the Mueller Microgrid

Before we propose a payment calculation scheme that fairly compensates mutual power transactions, Table 4 summarizes the production scenarios for the Mueller microgrid as obtained from the cost models presented in the previous chapters and distinguishes individual generation costs for the micro- and utility grid from standalone and joint operation.

Scenarios		Production (MW)		Individual generation cost ($/day)		Total generation cost ($/day)	
		Summer	Winter	Summer	Winter	Summer	Winter
{m} {U}		9.44 202,450	5.91 159,750	633 3,979,560	585 2,917,926	3,980,193	2,918,511
{m*} {U}		8.40 202,450	5.21 159,750	611 3,979,560	571 2,917,926	3,980,171	2,918,497
{m, U}	{m} {U}	60.62 202,397	0.00 159,755	1,636 3,977,701	0 2,918,015	3,979,337	2,918,015
{m*, U}	{m*} {U}	60.62 202,397	0.00 159,755	1,636 3,977,685	0 2,918,003	**3,979,321**	**2,918,003**

* indicates storage

Table 4. Generation scenarios and costs for model grids

Generation Scenarios and Cost Savings for the Power Exchange Coalition of Taipower Company and the Mueller Community

To support the findings of our joint generation analysis in Section 5.3, Table 4 shows that the microgrid produces 60.62 MWh at its maximum capacity at a cost of $1,636 during summer and produces nothing solely importing its energy needs from the utility during winter. We also find that microgrid storage infinitesimally reduces utility production during both summer and winter times. In the case of storage, the utility produces 202,397 MWh at a cost of $3,977,685 for the summer day and 159,755 MWh at a cost of $2,918,003 for a winter day. Thus, we find that the joint operation with controllable storage {m*, U} minimizes the total daily generation cost among all generation scenarios and constitutes as the best power exchange coalition.

Daily savings from joint generation can be calculated as the difference between the sum of individual and total generation costs and respectively account to $850 in summer and $494 in winter for the power exchange coalition {m*, U}. Comparing summer and winter savings, we find that the cost savings in summer roughly double the cost savings during winter. This is mainly due to the fact that higher demand levels during summer ask for bidirectional energy trading between the grids by deploying diversity features to maximize cost savings. However, during winter the utility generates the entire power for the interconnected system and one directionally exports energy to the microgrid.

Joint Generation Cost Allocation between Taipower Company and the Mueller Community

As discussed, a cost model for joint generation only allows to assess the value of a coalition but gives no hints on how to share it. Therefore, given the joint generation with power exchange we calculate the Shapley values to support an equitable division of costs and compensate for energy exchange through payments for mutual power transaction. Referring to our definition in Section 6.2, we calculate the Shapley values of a player as its net addition to the cost of a coalition (marginal cost) over all possible ordering of the players. Based on the individual and total generation costs of Table 4, the Shapley values for the coalition with storage {m*, U} are computed in Table 5.

	Summer (in $/day)		Winter (in $/day)	
Ordering	m’s share	U’s share	m’s share	U’s share
{m*,U}	*611*	3,978,710	*571*	2,917,432
{U,m*}	-239	*3,979,560*	77	*2,917,926*
Total	372	7,958,270	648	5,835,358
Shapley-Value (Average)	**186**	**3,979,135**	**324**	**2,917,679**
Total Joint Cost	*3,979,321*		*2,918,003*	

Table 5. Shapley values for the microgrid and the utility

In consistency with our findings in Section 5.4, Table 5 shows as represented by the Shapley values that the cost contribution of the microgrid is lower for the summer than in winter case. This is mainly due to the high penetration from solar power to reduce peak power loads, and the ability to dispatch distributed generation to avoid the generation of costly peak power plants during levels of peak demand. For the winter case, the microgrid only contributes a little to the coalition as the utility facilitates the total power generation and exports necessary power to the microgrid. Due to its high dependency on energy exports from the utility and lower solar power generation, we find a higher individual cost contribution for the microgrid in the winter case.

Fair Payment Calculation for the Energy Exchange between a Microgrid and the Utility

As the Shapley values express fair cost contributions of the micro- and utility grids to the coalition of jointly delivering an aggregated load schedule, this research adopts their calculation concept to support a fair compensation of energy exchange through mutual payments. We can calculate the fair payments for mutual power transactions as the difference of the Shapley values and the actual generation cost of each grid under joint generation. In other words, applying the Shapley value helps to reconcile for an equitable allocation of operation costs and transaction payments for energy exchange between the systems. Table 6 compares the actual generation costs from individual production under joint operations with their cost contribution determined by the Shapley values:

	Summer (in $/day)		Winter (in $/day)	
	m’s share	U’s share	m’s share	U’s share
Actual Production Costs	1,636	3,977,685	0	2,918,003
Shapley-Value	186	3,979,135	324	2,917,679
Daily Payment	-	1450	324	-

Table 6. Actual generation cost and daily payments for power exchange

We can see that during summer days the actual production costs of $1,636 of microgrid generation heavily exceeds the Shapley value of $186. This is mainly due to the reason that the microgrid helps to reduce total system loads by generating at maximum capacity to avoid commitment from utility peak power plants during the summer day. Additionally, the “service” to provide a high penetration of renewable energy generation which are included as negative loads and the control over the maximum number of PHEVs to discharge power during peak demand periods lowers its Shapley value. As a result, the microgrid is compensated for its activities by the utility in the summer scenario and receives $1,450 per day for its power transactions.

On the contrary, during winter times the microgrid fully depends on the import of power from the utility as total system load are too low to ask for its unit commitment and power from renewable generation are not enough to self-sufficiently supply its daily power needs. Apparently, Shapley values for the microgrid during winter are higher as it fully depends on the imports from the utility grid. Therefore, during winter times the microgrid pays $324 for its energy imports to the utility.

In summary, we suggest an interconnection between the Taipower Company and the Mueller microgrid to analyze cost savings from joint generation through energy exchange and calculate fair payments to compensate mutual power transaction for a summer and winter generation scenario. Due to variations in seasonal load profiles, we find different results for summer and winter when analyzing the energy exchange between the micro-and utility grids. For higher demand levels in summer, a bidirectional flow of energy minimizes joint generation costs by mutually trading-off time-varying generation costs between the grids. For lower utility generation costs during winter, however, joint generation scheduling only concerns about the utility production and a one directional power flow from the utility grid to the microgrid to maximize joint savings.

The Shapley values show that the microgrid cost contribution is lower in summer due to its high penetration from solar power and ability to dispatch distributed generation which profoundly contribute to reduced joint generation costs. For the winter case, microgrid cost contributions are higher due its dependency on energy exports from the utility and lower solar power generation. Our proposed payment calculation scheme calculates fair payments for power transactions as the difference between the Shapley values and the actual generation cost of each grid under joint generation transactions. In consistency with our findings, the utility pays the microgrid for its high contribution to joint savings during summer as microgrid production costs heavily exceed its Shapley value. However, during winter the microgrid pays the utility for importing all its energy needs to support joint savings.

Chapter 7

Conclusions

The integration of changing technologies and new entrants in the electricity market ask for possibilities of energy exchange that allow to cooperatively gain and share the benefits from available generation resources. In this regards, microgrids that generate power locally in proximity to the loads and can be controlled as a single entity can pose significant cost saving benefits through joint operations with the existing power system.

This study has examined the joint operation of a microgrid and its utility network, and suggested a method to fairly compensate for energy exchange through payments for mutual power transaction based on the individual contributions to reduced daily generation costs when micro-and utility grids agree to collaborate as a single entity where generation was centrally dispatched. For this purpose, we have assumed a privately-owned microgrid interconnected with its hosting utility and developed a centralized decision model to optimally minimize of shared generation costs.

To address the problem, the decision model was inserted into the overall architecture of a single microgrid and a utility grid with fixed system configurations and deterministic input variables that considered the electrical load profiles, microgrid and utility generation constraints, ambient conditions and economic generation data. The decision model presented here was implemented in CPLEX as mixed-integer programming with second order cost functions. ILOG's CPLEX 12.2 helped to effectively solve the problems instead of using standard algorithms.

To fairly compensate for energy exchange through payments for mutual energy transactions, we first calculated the "as-if" standalone generation costs for both the microgrid and the utility grid based on the minimized cost of their individually owned generation units with no power exchange between the systems. We then compare the cumulative cost from standalone dispatch with the actual cost under pool dispatch to provide a proper basis to fairly allocate joint operation costs. Justified by its favorable properties to support a mutually agreeable division of joint operational costs, finally, the Shapley value was applied to fairly compensate for power exchanged and calculate the payments for power transactions between a microgrid and its hosting utility.

In a case study on the model interconnection of the Taipower Company and the Mueller microgrid we showed that system operation costs can be reduced by minimizing daily operation cost through energy exchange and justified that a method to calculate fair payments for mutual power transactions is needed.

With the knowledge that there are additional cost saving benefits from the joint operation of a microgrid and its hosting utility, future works need to find ways to address the following issues not yet addressed in this research:

1. include both the cost of supplying thermal and electrical loads to include the efficiency gains from combined heat and power systems (CHP) in microgrids [Bra14]
2. include probabilistic models to account for the cost of meeting demand with a certain degree of reliability that is appropriate for the value of load being served, e.g. by including risks from system blackouts in utilities and intermittent renewable generation in microgrids that add to daily operation costs [Bia96] [RaH09]
3. study different coalition formation algorithms (e.g. bilateral programming or auction mechanisms) for the energy exchange between micro- and utility grids that facilitate a proper basis to fairly distribute the savings from joint operations
4. include operation decisions that consider indefinite dispatch scenarios over a longer time period which consider investment costs as important for long-term operation decisions [Haw10]
5. correlate renewable energy generation with storage devices to account for the 'added-value' from storage-coupled PV generation instead of considering storage on its own when renewable generation is considered as negative system loads [FLK13]

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