Grid-Connected Renewable Energy Systems for Residential HVAC Load Management

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GRID-CONNECTED RENEWABLE ENERGY SYSTEMS FOR RESIDENTIAL HVAC
LOAD MANAGEMENT

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Master’s Program in Electrical Engineering

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GRID-CONNECTED RENEWABLE ENERGY SYSTEMS FOR RESIDENTIAL HVAC LOAD MANAGEMENT

by

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THESIS

Presented to the Faculty of the Graduate School of
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Abstract

With an ongoing mission of utility operators to maintain a resilient and reliable power grid in the face of continuously increasing load demand, it is essential that advancements be made in developing both technology and methodology to help account for the increasing energy requirements. According to the U.S. Department of Energy (DOE) and Energy Information Administration (EIA), the residential end-use sector alone counted for 22% of all electricity used in the U.S. in 2020. Of this, approximately 32% of household electricity load is the direct result of air conditioning and space heating units (HVAC). One way to account for this load involves the concept of load targeting through grid-connected energy such as distributed energy resources (DERs). Both solar photovoltaic (PV) and wind turbine energy have made significant advancements in both production capacity, efficiency and cost effectiveness that can be applied to supplement the necessary load required by residential HVAC. The work described in this thesis focuses on the integration of roof-top solar generation and both offshore and onshore wind turbines to effectively account for this portion of the residential sector. The proposed methodology categorizes the entirety of the continental U.S. as separated into five distinct climate regions and the most affecting parameters respective of each DER being modeled to determine the equivalent electricity requirement to counteract the load being observed.

The major contributions of this thesis move to examine the potential load reduction of applying DERs in a partial load targeting fashion while also observing the effectiveness of each resource being observed. Chapter 3 contributes to the development of (i) a detailed analysis for modeling household HVAC load using tailored PV arrays; (ii) a methodology that requires significantly fewer PV panels than whole load targeting as is presently being pushed by the solar power industry; (iii) a load curtailment solution applicable to most U.S. households. Chapter 4
contributes to the development of (iv) a detailed analysis for modeling U.S. residential loads using wind turbine technology; (v) An assessment for observing the potentials of both offshore and onshore technology when targeting identical loads. Both chapters simultaneously contribute to (vi) evaluate residential HVAC load characteristics pertaining to specified climate areas using simple mathematic evaluations; (vii) cover a nation-wide benchmark of testable areas and scenarios. Moreover, the results of modeling these systems help to demonstrate the effective load-shedding potential that can help utility operators alleviate grid stress while maintaining end-user quality of life by not requiring significant daily changes in HVAC management. The work based on this thesis is supported by the National Science Foundation (NSF) and DOE.
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Chapter 1: Introduction

1.1 Background and Research Motivation

In recent years, major advancements in renewable energy technology have brought upon opportunities to help account for increasing load demands. Amongst these technologies, solar and wind energy have most significantly developed their presence in power grid infrastructures, both in rated power production capacity and grid integration. Wind energy alone has developed into the most prevalent utility-scale source of renewable energy with its share of total power produced in the U.S. growing from nearly 1% to 9.2% in the past 30 years [1]. Since 2019 alone, wind power generation saw an increase in presence of 14% and is expected to continue growing [2]. Along a similar timeline, the advancement of PV technology has also placed itself amongst the top of renewable energy technology with its substantial increase in nameplate capacity and efficiency whilst costs continue to drop. The consequence of these technologies, however, are their inconsistencies as a result of their inherent nature and varying affecting factors and are thus, better suited to providing supplemental energy for the time being as opposed to replacing more stable means of power generation such as nuclear plants. Fortunately, both wind and solar energy still provide a significant opportunity for countering the increasing load demands and thus providing an additional means for maintaining grid resiliency. Endeavors for encouraging the push into greener energy practices make the application of these DERs all the more worth exploring.

1.2 Identification of Problems and Rationale of Study

As the electricity consumption in the U.S. continues to expand, utility operators continuously balance production with an ever-growing need for load shedding solutions. To do this effectively, advancements in both technology and methodology must be adopted in order to
combat the growing demand. An efficient way of discerning what areas could require attention is to isolate specific areas of concern in order to promote a greater whole. One such area lies within the residential energy sector or, more specifically, the most demanding electricity load attributed to it. As per studied done by the U.S. EIA along with the DOE, approximately 22% of U.S. energy consumption occurred in the residential sector in year 2020 [3]. Space heating and air conditioning utilities amounted to a combined 32% of electricity consumed in the same sector in 2015 at 15% and 17% respectively and is expected to gradually increase. According to the EIA, a major factor influencing the increasing load demand comes from the number of central air conditioning units having more than doubled since 1980 [4]. While demand response programs may offer opportunity to persuade end users to adopt more lenient habits in their use of space heating and air conditioning, consumers are expected to want to maintain the quality of life they have adapted to and continue indulging in this practice. To effectively curtail utility strain caused by HVAC-related load, the methodology would be most successful in providing minimal impact on end-user quality of life.

Hence, development into the concept of partial-load targeting through the use of supplemental energy by way of DERs offers an effective means of applying relatively easier and lower maintenance power generation capable of generating the capacity required for specified loads throughout various areas of the U.S. Doing so will also help to relieve load-demand stresses placed on power system operators as well as provide new systems in the study of DER control and the development of demand response programs.

1.3 **Scope and Limitations of Study**

The major scope of this thesis is to promote a general approach of targeting the portion of U.S. load caused by heating and air conditioning elements within the U.S. residential sector through deriving models of both onshore and offshore wind turbine technology as well as solar PV
panels. This is done through utilizing average annual household load criteria as provided by 2015 EIA Residential Energy Consumption Survey (RECS) data attributed to five predetermined climate regions. Select portions of this data are then aggregated to develop heating and cooling profiles for the average U.S. household as determined by EIA simulations conducted using the National Renewable Energy Laboratory (NREL) Building America House Simulation Protocol’s B10 benchmark house. RECS data offers load profiles specific to climate data as designated by U.S. DOE. These profiles are used to categorize the five case study regions being observed in this series of work. Chapter 3 covers a PV scenario involving a reference panel and the five associated climate regions. Chapter 4 covers two wind energy scenarios – onshore and offshore – involving two different reference turbines and the five associated climate regions.

The following are the limitations of this thesis.

- Household data referenced from RECS survey consists only of the average household load.
- Test cases generalized to provide nation-wide range of analysis.
- PV panel azimuth and tilt are not considered in the scope of this research and are expected to be further evaluated at a case-by-case basis.
- Neither commercial nor industrial HVAC loads are studied in this thesis.
- The economic feasibility of the DER implementations are not studied in this thesis.
- Offshore wind capacity factors are estimations as per the International Energy Agency.

1.4 **Goal and Objectives**

The goal of this thesis is to explore the application of DERs to provide supplemental energy to target a specified gross load. This involves developing both solar arrays and wind farms to each
be capable of completely supplying the target load on their own accord. This involves developing programs that apply accurate sizing methods to estimate the actual quantities of each DER model for a given household or region followed by calculating their estimated annual production. In order to achieve this, the following objectives are carried out.

- **Objective 1: Determining generalized method for observing nation-wide residential HVAC usage.**

  This objective aims to provide case studies that can be used when observing the development and modeling of DER systems and the reference loads they are targeting. This objective is carried out by applying load data sourced from empirical studies carried out by international and government affiliated organizations that produced datasets pertaining to information observed in this study.

- **Objective 2: Develop technique for reducing grid stress during peak demand without directly affecting consumer HVAC usage.**

  This objective aims to enact methodology that can improve grid robustness while simultaneously maintaining end-user quality of life by not requiring changes to their usual space conditioning practices. To achieve this, emphasis is placed on the installation of DER systems tailored to handle the specific loads produced by the various end-user HVAC systems.

- **Objective 3: Determining reliable sizing methods for developing DER systems when targeting isolated loads.**

  This objective studies different aspects of sizing functions for both solar and wind energy including factors involving site surveying, various affecting parameters, historical data, and literature. For solar, a series of calculations developed with reference to viable
academic literature are carried out for determining the PV sizing functions. For the wind portion, the application of capacity factor data is used to calculate the aggregate turbine sizing functions as it fosters the use of both historical data and practical estimations that could represent large regions of areas.

- **Objective 4: Evaluate the feasibility of DER supplementation for partial load targeting.**

  The outcome for this objective is to analyze the resulting systems proposed by programming software to account for the loads targeted by the DERs. This objective is achieved by developing and observing system sizes recommended by the software for various climate regions to determine the practicality of said systems.
1.5 **Organization of Thesis**

This thesis consists of 5 chapters in total and is organized as depicted in Figure 1.1. This section details the structure of the thesis with a brief description of the major chapters.

![Figure 1.1: Organization of Thesis.](image)

- Chapter 2 presents a comprehensive literature review that discusses relative research surrounding a similar scope as presented in this body of work. Such topics include the application of PV and wind turbine technology of different sorts aimed at supplementing various loads. Concepts exploring the use of solar PV, offshore and onshore wind turbine technology are explored in this chapter.
- Chapter 3 presents a technical analysis for targeting residential HVAC loads using tailored household PV systems. The chapter proposes a methodology for developing multiple
ranges of systems for virtually all residential household within the continental U.S. The model develops ranges of PV panel requirements depending on the climate region with respect to solar irradiance levels before simulating the potential power production output of each system. Resulting load curtailment is then analyzed to determine effectiveness.

- Chapter 4 presents a concept for modeling residential HVAC loads using offshore and onshore wind technology. This chapter uses programming code to develop a series of turbine systems to account for the aggregated target load specific to the climate area being observed. The chapter also compares the load curtailment potential between offshore and onshore technologies. *It is to be noted that research findings of Chapters 3 and 4 contribute to fulfill the Objectives 1-4 of this thesis.*

- Lastly, Chapter 5 summarizes the major findings and contributions of the thesis as well as provide direction for potential future work.
Chapter 2: Literature Review

This chapter aims to explore literature pertaining to relative application of DERs for load targeting as well as assessments and evaluations of both existing and future projects.

2.1 Solar and Hybrid Energy

Multiple case studies have been conducted on the effects of implementing solar PV generation on single, large building sites such as apartment complexes, commercial structures, or university buildings. Good examples of this are covered by Ghenai et al. [5], where they presented analysis on a hybrid system model for an administration building at the University of Sharjah, and Al-Refai et al. [6] studied a grid-connected PV system for a department at the university of Tripoli in Libya. These studies aimed to target the entirety of the load consumed by the building they are interconnected to. Alternatively, other cases aim to absolve specific portions of a structure’s electricity load through targeting components of it such as heating, ventilation, and air conditioning (HVAC) systems. In reference [7], a comparison of a combination of these methods is presented to determine effectiveness of each method. Another approach involves implementing new technologies and methodologies that help manipulate the load profile and the way it is managed. In reference [8], a PV system is used to power a proposed chilled-water cooling system for a health care facility. Moreover, a solar-powered air conditioner that operates on a solar heat-driven refrigeration system is discussed in [9]. Other methods were suggested to consider HVAC load in demand response programs [10], or utilizing smart technology to optimize HVAC load [11].

2.2 Onshore Wind Energy

Several case studies have explored both the endeavor and effects of integrating wind turbines into the current infrastructure through multiple facets. Some example concepts consist of integrating hybrid energy systems that include wind and solar technology to target a specified load
Others focus primarily on the sole application of wind turbine technology as a means to target specified loads such as seen in [14] where a group of different turbines are tested over different case sites for optimal goodness of fit. Many studies also aim at foreseeing the risks and optimization endeavors of the integration of future and preexisting wind farms into the power grid. For example, in [15], turbines connected to residential feeders are outfitted with an active power curtailment strategy to avoid overvoltage issues. Gonzalez-Langatt [16] studied the impact of various transmission line applications to determine optimal power quality when connecting to the La Guajira wind farm. In addition to the major factors surrounding the effective function of wind farms, research is also conducted into determining optimal hub height such as Songtao et al. [17] reported a study about turbine power production for areas of business and residence. These cases are predominantly driven by onshore technology due in part to a greater ease of accessibility for both physical units and project space when compared to its offshore counterpart.

2.3 Offshore Wind Energy

With greater advancements being made in the world of offshore technology, more emphasis is being placed on similar implementation factors such as wind farm sizing, turbine model selection and more. However, offshore integration also comes with additional factors to be studied in the realm of interconnecting to a robust transmission system and physical requirements for the harsher environment. For example, Wang et al. [18] scrutinized the early developmental status of China’s offshore standings. Early research from [19] provided in-depth analyses on the developmental aspects of implementing offshore wind farm projects around the world and countermeasures expected to be taken. Furthermore, more research has been conducted on the integration and potential impact of aforementioned projects into power grids [20], [21]. More specifically, reference [22] provided an assessment of several European-based offshore wind farms.
and the challenges of integrating into the transmission network. Reference [23] explored the concept of integrating offshore wind farms into corresponding offshore oil and gas platforms as a means of lowering operation costs while also maintaining robustness and decreasing fuel usage. Similar to onshore projects, multiple turbine models offer the ability of maximizing energy production through determining the optimal goodness of fit. Reference [24] proposed an analytic hierarchy process that produces an optimal turbine selection based on applying a multi-layer model and judgement matrix.

A common concept shared between both onshore and offshore applications is developing projects with the optimal equipment and location to produce the highest possible capacity factors. Doing so results in more attractive projects that may later be deemed worthy of funding and construction. Ghajar et al. [25] introduced a method for optimal site matching of turbines based on capacity and a select set of factors associated with various turbine models. Both references [26] and [27] proposed turbine selection strategies through the use of reference capacity factor curve information.

2.4 SUMMARY

Chapter 2 provided a detailed literature review on concepts relating to the application of DER technology in multiple facets pertaining to supplying power to specified loads. Both solar and wind turbine analyses were discussed in regard to development, technical aspects, and performances.
Chapter 3: Integrated Photovoltaic System for Modeling Residential HVAC Loads

3.1 INTRODUCTION

This chapter presents a technique for targeting the portion of U.S. residential load brought upon by air conditioning and heating elements by using PV systems tailored to the average household across five climate regions. The proposed method utilizes empirical data backed by various government affiliated organizations and solar irradiance data to size and evaluate PV systems to support the electrical load requirements caused by the heating and air conditioning components in housing within all major U.S. climate regions. This is done through applying programing software to accurately size and simulate the power production of the derived PV systems.

3.2 PROPOSED APPROACH FOR HVAC SOLAR PV DESIGN

An itemized flow diagram is conceptually illustrated in Fig. 3.1 for the proposed methodology comprising of two major sections: sizing the PV array and simulating the resulting system strictly through a mathematical algorithm and using parameters provided by empirical studies and reputable organizations. This begins with first determining the initial PV array requirement using a preliminary sizing function. This function operates using the target hourly load data, solar radiation values and a select performance ratio. The resulting raw system size is then reprocessed through a finalization function using PV module parameters. Finally, with the true system being determined, the system is simulated using the regional irradiance levels and performance ratio to forecast the estimated power production over a certain period of time. Because this work considers annual load data, the forecasting function will also be adjusted to provide an annual generation profile. The functions outlined in Fig. 3.1 are further detailed in the following section.
3.2.1 PV System Sizing

Accurately sizing a solar PV system of any type involves first calculating a more specific, raw, system size to be used as reference when determining the number of solar panels needed. This begins with calculating the daily power demand of a household using a known annual average load. For the purposes of targeting the heating and cooling elements of the household, the aggregated annual load of these elements is used in place of the total household load. This partial load is evaluated against the solar irradiance levels within the test region as well as a performance ratio parameter which accounts for the irregular production behavior inherent of PVs. NREL studies determined a performance ratio of approximately 77.3% under PVs for utility scale application (PV USA) test conditions for solar power generation \[28\]. The following equation is used to determine a raw system size requirement \((SR_n)\) in kW \[29\].

\[
L_D = \frac{L_{TH}}{365 \text{ days}} \quad (1)
\]

\[
SR_n = \frac{L_D}{i_n \Phi} \quad (2)
\]

where \(L_{TH}\) is the average annual load in kWh/year, \(L_D\) represents the daily load value of the target load in kWh/day, \(\Phi\) is the NREL performance ratio, and \(i_n\) is the average solar irradiance level in that particular area in sun hours. To determine a true PV system size, this raw value is recreated.
using the rated power of the intended solar panels with the result of equation (3) rounded up to the nearest whole panel size. This value is then multiplied by the rated power to determine a true system size.

\[ Pan_n \approx \frac{SR_n}{P_m} \]  

\[ ST_n = Pan_n \times P_m \]  

where \( Pan_n \) is the number of PV panels, \( P_m \) is the rated power of the solar panel in watts and \( ST_n \) the true system size in kW. True PV system sizes are designated across all solar radiation levels of a given region. This produces a handful of different PV system sizes per region.

3.2.2 PV System Modeling

Solar PV power systems are measured in kilowatts and therefore require calculation to determine an estimated annual energy production value. This value is used to measure the overall production of the system including potential losses that may accrue over the course of the year. The application of irradiance levels, true system sizes and the estimated performance ratio is expressed in (5) [29].

\[ PG_n = i_n \times ST_n \times \Phi \times 365 \text{ days} \]  

Because we are referencing annual load data, the equation is multiplied by 365 to account one full year’s worth of estimated power generation (\( PG_n \)) in kWh/year.

3.3 Simulation Results and Analysis

The method proposed in this chapter applies a MATLAB program to process all initial data being considered and evaluate an array of resulting system sizes. The program then plots the resulting range of evaluations into a plot containing power generation, target load and total PV panels with respect to solar irradiance.
3.3.1 Initial Load Development

The average annual load data for both total household and aggregated HVAC is acquired from the EIA RECS [30]. The datasets are developed through studies utilizing a benchmark home outfitted to represent the average base-load U.S. household [31]. These are used as base representations for the average electricity load demand found in each of five corresponding climate regions. These climate regions are determined using the DOE Building America Climate-Specific Guidance (BACSG) and include Cold/Very Cold, Mixed-humid, Mixed-dry/Hot-dry, Hot-Humid and Marine [32]. To determine the solar radiation within each climate region, the climate map provided by the DOE was compared to the NREL horizontal irradiance map [33] and national solar radiation database [34] to determine an accurate range of irradiance levels, or sun hours, normally expected of each region. Table 3.1 contains the initial parameters presented in this section.

<table>
<thead>
<tr>
<th>Case</th>
<th>Climate region</th>
<th>Total Annual Load (kWh)</th>
<th>Heating and Cooling Annual Load (kWh)</th>
<th>Solar Irradiance Range (kWh/m²/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very cold/cold</td>
<td>8,913</td>
<td>4,274</td>
<td>4.00 – 5.25</td>
</tr>
<tr>
<td>2</td>
<td>Mixed-humid</td>
<td>12,302</td>
<td>6,383</td>
<td>4.25 – 5.00</td>
</tr>
<tr>
<td>3</td>
<td>Mixed-dry/hot-dry</td>
<td>7,651</td>
<td>3,474</td>
<td>5.25 – 6.50</td>
</tr>
<tr>
<td>4</td>
<td>Hot-humid</td>
<td>13,805</td>
<td>6,756</td>
<td>4.75 – 5.25</td>
</tr>
<tr>
<td>5</td>
<td>Marine</td>
<td>9,596</td>
<td>3,853</td>
<td>4.00 – 5.75</td>
</tr>
</tbody>
</table>

3.3.2 Simulation Data and Parameters

For simulation purposes, a solar panel that is currently being marketed for household solar installations is considered. The Panasonic EverVolt Series EVPV360 solar panel has a rated power
of 360 W and a module efficiency of 20.6% [35]. This panel will be used for determining true system sizes, as systems are normally sized using the number of panels intended to be installed. Normally, parameters for tilt and azimuth are also considered in developing PV generation systems. However, because the work of this chapter considers a vast array of PV systems across several different potential building structures within the residential area, these parameters are not specified. The data is hence further generalized and can be expected to be elaborated in better detail when analyzing a house-by-house scenario. In addition to these assumptions, the previously defined performance ratio determined by NREL is evaluated under PV USA test conditions in order to better represent real-world conditions and thus provide more accurate data returns [28].

3.3.3 Result Analysis

Results of simulating the proposed PV systems using the aforementioned forecasting function are displayed for each test case in Figs. 3.2 - 3.6. Each plot demonstrates estimated solar generation spanning the irradiance range derived for each case in increments of 0.01 kWh/m²/day; hence case 1 simulates 126 iterations between 4.00 and 5.25 sun hours. The panel number of each system is represented in the grey shaded plot. The program simulates hundreds of iterations with respect to iterations based on irradiance level. The rounding component of the finalization function helps to significantly condense the amount of different system sizes produced in order to conform to a more realistic design. For example, Fig. 3.2 demonstrates three potential system sizes of 3.24 kW, 3.60 kW, and 3.96 kW using 9, 10, and 11 panels, respectively. The stepping behavior of each plot is determined by the finalization function choosing where a panel within the system may be added or removed. Furthermore, each step shows the estimated power generation range per number of panels in a system within its calculated irradiance range. The dotted line represents the average annual solar radiation for the HVAC components as provided by EIA datasets.
Figure 3.2: Case 1: Very cold/cold climate region estimated PV system generation.

Figure 3.3: Case 2: Mixed-humid climate region estimated PV system generation.
Figure 3.4: Case 3: Mixed-dry/hot-dry climate region estimated PV system generation.

Figure 3.5: Case 4: Hot-humid climate region estimated PV system generation.

Figure 3.6: Case 5: Marine climate region estimated PV system generation.
A common attribute between all systems is found in the behavior of the estimated power generation. When compared to the average load brought upon by the HVAC components, the generation of each system is never estimated to fall below this load average. This is due to the program finalization function observing when more power generation is required to meet the demand of the target load. When it is determined that more power generation within a specified solar radiation range is required, an additional solar panel is added. Fig. 3.5, for example, demonstrates this well at approximately 5.12 sun hours. At a higher irradiance value, it is projected that only 13 panels are required to maintain a power generation above the minimum load required of 6756 kWh. However, once irradiance falls below this value, the function recommends an additional panel be added. The resulting system sees an increase of 360 watts and the current irradiance value becomes the high end of the power generation for this particular system.

Simulations returned multiple arrays of potential system sizes and production levels for each region dependent on the sun hours of a given location. Further observation of these arrays returned percentage values of HVAC load generated at each iteration. Comparing these values to annual household electricity load provides the total annual load shedding potential of the proposed systems. Table 3.2 contains condensed simulation results for each test case. As may have been expected, regions experiencing higher average irradiance levels required the smallest PV systems in order to produce enough energy to satisfy the target load. Case 3 provides the best example of this in that even with the smallest PV systems between all cases, the systems are still capable of producing nearly 17% in excess energy compared to the target load, as seen in Fig. 3.4. Consequently, the importance of solar radiation as a heavily affecting parameter in PVs can be seen in Fig. 3.3. Due to lower average annual irradiance levels, systems within the mixed-humid climate region are required a much higher range of solar panels – from 13 to 15 – in order to reach
consumption levels of their space conditioning system. Similar to case 2, the hot-humid client also operates on the same range of solar panels. Data from Table 3.2 suggests these two climates maintain a significantly higher average annual load requirement than the other three climate regions. This suggests some correlation between humidity and power demand.

Table 3.2: Comparison of Simulation Results Between Test Cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Climate region</th>
<th>Panel range</th>
<th>HVAC load generated (%)</th>
<th>Estimated household load removed (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very cold/cold</td>
<td>9 - 11</td>
<td>100.05 - 112.29</td>
<td>47.98 - 53.84</td>
</tr>
<tr>
<td>2</td>
<td>Mixed-humid</td>
<td>13 - 15</td>
<td>100.03 - 107.60</td>
<td>51.90 - 55.83</td>
</tr>
<tr>
<td>3</td>
<td>Mixed-dry/hot-dry</td>
<td>6 - 7</td>
<td>100.17 - 116.66</td>
<td>45.48 - 52.97</td>
</tr>
<tr>
<td>4</td>
<td>Hot-humid</td>
<td>13 - 15</td>
<td>100.07 - 107.56</td>
<td>48.97 - 52.64</td>
</tr>
<tr>
<td>5</td>
<td>Marine</td>
<td>7 - 10</td>
<td>100.02 – 114.09</td>
<td>40.16 - 45.81</td>
</tr>
</tbody>
</table>

After calculating the average annual production of each system, it is approximated that the resulting load shed amounts to an average of 49% of total household load across all climate regions. Of the five cases tested, the mixed-humid climate region is suggested to have the highest potential with an average total household load removal of 53.69%. Alternatively, the marine climate region sees the lowest potential household load removal at a combined average of approximately 42.63%. When looking at the hot-humid and mixed-humid regions, the results of identical PV system sizes return different load removal percentages. Although the hot-humid climate is associated with a higher peak solar radiation level, their highest potential load reduction
percentage is lower than that of the mixed-humid region with lower irradiance levels. This is the result of the latter region’s lower total annual load requirement in comparison.

3.4 SUMMARY

This Chapter-3 presented a novel approach for negating the electrical load brought upon by residential HVAC through the use of custom-tailored PV arrays. A series of functions and affecting parameters were applied using programming software to determine the appropriate number of PV panels required per household in every major climate region. Simulation results suggest a significantly smaller number of PV panels required than the average rooftop array used for whole load targeting as well as a potential for removing roughly 49% of total household load across all climate regions in the mainland U.S. The chapter also demonstrated five case studies pertaining to the five climate regions being observed and an analysis on the production requirements of each.

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1 Research findings of this chapter have been accepted for publication in peer-reviewed conference indicated below: O. S. Acosta, P. Mandal, E. Galvan, and T. Senjyu, "Integrated Photovoltaic (PV) System for Modeling Residential HVAC Loads – Technical Analysis," in Proc. 2022 IEEE Power & Energy Society General Meeting (PESGM2022), July 17-21, 2021 (Accepted).
Chapter 4: Integrating Offshore and Onshore Wind Energy to Model Residential HVAC Loads

4.1 INTRODUCTION

This chapter presents a technical analysis for modeling the electrical demand of residential HVAC loads using aggregated wind turbine technology – both onshore and offshore. The proposed model utilizes empirical data backed by various government affiliated organizations and both historically recorded and theoretically estimated capacity factor levels to determine the number of turbines required to support the electrical load requirements caused by the heating and air conditioning components in housing within all five U.S. climate regions being observed. This is done through applying programming software to accurately size and simulate the power production of the aggregate turbine arrays that are derived.

4.2 PROPOSED APPROACH FOR AGGREGATE TURBINE DESIGN

4.2.1 Data Assumptions

For simulation purposes, two wind turbines that are commercially circulating in the wind turbine industry are considered for this study. For simulating the onshore scenario case set, the Vestas V100 model with a rated power value of 2.0 MW is selected [36]. This turbine model is selected due to its current utilization by several onshore wind farm projects within the U.S. including the Goodwell Project, Border Winds Project, Courtenay, and others [37]. For simulating the offshore scenario case set, the 13 MW, GE Haliade-X model is considered [38]. This is a relatively newer model turbine model designed to target offshore applications. The Haliade-X models are expected to be utilized by offshore projects Vineyard Wind 1 and Ocean Wind, both of which are currently in development in Massachusetts and New Jersey, respectively [39] [40]. Normally, parameters referring to site surveying and hub height would be considered when
developing wind farm projects. However, because the research conducted in this thesis covers a vast array of land and building site potentials, these parameters are not specified. The data is therefore further generalized and is assumed to be further elaborated on in better detail when analyzing scenarios at the project level. Additionally, the application of annual capacity factor as a most affecting parameters – acquired both through historical data and estimations – helps to better represent realistic potential and thus provide more accurate data returns.

Figure 4.1: Diagram of proposed algorithms for developing offshore and onshore energy generation systems and resulting power production estimation.

4.2.2 Proposed Methodology

The general approach being discussed in this chapter is illustrated in Fig. 4.1. This begins in the aggregate turbine sizing phase by referencing two types of wind turbine to be represented in onshore and offshore application. These turbines were selected due to their current representation in commercial environments as well as prospective integration in future projects. Both onboard and offboard scenarios are attributed a range of CFs to be considered to calculate regional capacity yields using a tailored MATLAB program. From here, an array of estimated annual power production values is calculated incrementally with respect to the corresponding CFs. This array of sizes is then plotted and compared to the regional residential HVAC load requirement associated
with each individual climate case for analysis and to determine the resulting load curtailment within the load comparison phase. Furthermore, the resulting data allows for additional observations to be made between the onshore and offshore case scenarios. This helps to create a more in-depth analysis when determining effectiveness and feasibility at a case-by-case basis.

4.2.3 Aggregate Turbine Sizing

To determine the aggregate number of turbines required to account for any specific load, extensive site surveys are normally conducted along with analysis regarding model efficiency and a variety of forecasting methods that take advantage of historical wind speed data. This method is most effective when considering individual wind farm projects specific to their own individual locations. However, the scope of this study covers an aggregated potential of wind turbines that spans a much larger land mass than an individual project study. For this reason, this chapter instead considers capacity factor data in order to estimate yearly electricity production for both onshore and offshore scenarios. The following equation is used to equate the residential HVAC load required by each region with the equivalent aggregate turbine model.

\[ X_t \times W_{\text{rated}} \times CF \times 8760\text{hours} = L_{\text{HVAC}} \times H_{\text{total}} \]  

(1)

Where \( X_t \) is the total number of turbines, \( W_{\text{rated}} \) is the rated power production per turbine in kWh, \( CF \) is average annual capacity factor, \( L_{\text{HVAC}} \) is the average annual residential HVAC load per region is kWh, and \( H_{\text{total}} \) is the total number of housing units per climate region. To determine a true turbine value, the total aggregated residential HVAC load for the region is calculated before using the remainder of the equation to solve for \( X_t \). This value is then rounded up to the nearest whole turbine value to determine a true aggregate sizing.
4.2.4 Load Comparison

The resulting value of turbines per CF is recalculated into equation (1) to evaluate a total projected power production value. The nature of the function for the proposed methodology attempts to either exceed or at least match the equivalent annual target load that it is being evaluated to account for. Because of the large deviation between a single, typical turbine’s power production capabilities and the estimated annual residential HVAC load for an entire climate region, the excess power production from an addition turbine is expected to be minimal in the aggregate.

4.3 Simulation Results and Analysis

The method proposed in this chapter applies a MATLAB program to process all initial data being considered and evaluate an array of resulting system sizes. The program then plots the resulting range of evaluations into a plot containing power generation, target load and total turbines with respect to CF.

4.3.1 Initial Load Development

The average annual load data at the residential sector for both total household and combined HVAC components is obtained through the EIA RECS [30]. The datasets being considered are developed through empirical studies that utilize a benchmark representational home that is outfitted to meet the average U.S. household’s base load [31]. To further elaborate, each dataset is represented through different means including categorization based on five predetermined climate regions. The climate regions being observed were developed using the DOE BACSG to include the following categories: Cold/Very cold, Mixed-humid, Mixed-dry/Hot-dry, Hot-Humid and Marine [32]. To determine the capacity factor ranges being analyzed for onshore scenarios, the BACSG reference map for climate areas is overlayed with average annual CF data.
provided by the DOE WINDExchange archives [41]. These archives contain average annual capacity factors sourced from all existing onshore wind farms in the U.S. and categorized by state. Each case scenario contains a collection of these average CF values and is attributed with a range between the absolute lowest and highest values recorded to provide realistic expectations within each region based on recorded historical evidence. This creates five unique and realistic ranges to be observed when determining the number of onshore turbines required to account for each case’s target load. It should be noted that current availability of wind farms in the Southeastern U.S. are lacking when compared to the rest of the country. This directly effects the historical data availability for capacity specific to the Hot-humid region of Case 4. To help account for this, the data available to this region is expanded upon by providing a range that spans from a maximum of 36%, as demonstrated in the DOE data, down to a 30% potential for purposes of providing a broader range of realistic potential. This range is significantly smaller than the recorded ranges used for other climate regions and is expected to reflect as such when plotted.

The offshore scenario uses a different approach to develop a CF range. Due to the borders used to designate each case region, all five cases have offshore access and thus a potential for offshore wind farms. However, the U.S. currently lacks a viable source of historical CF data due to a very small number of currently operating offshore wind farms. Instead, theoretical CF are taken into consideration. The International Energy Agency (IEA) offshore wind outlook of 2019 attributes advancements in wind turbine technology within the industry to the growth of offshore wind capacity, suggesting that current average annual capacity for offshore wind ranges between 29% – 52% and is expected to continue growing [42]. This estimated range is considered for the purposes of offshore calculations for all five climate regions. Table 4.1 presents the initial parameters discussed in this section.
Table 4.1: Climate-Based Case Studies and their Initial Parameters

<table>
<thead>
<tr>
<th>Case</th>
<th>Climate region</th>
<th>Total housing units (million)</th>
<th>Average Household HVAC (kWh)</th>
<th>Total Aggregated (TWh)</th>
<th>Existing Onshore (%)</th>
<th>Estimated Offshore (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very cold/Cold</td>
<td>42.5</td>
<td>4,274</td>
<td>181.645</td>
<td>22 - 44</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Mixed-humid</td>
<td>33.5</td>
<td>6,383</td>
<td>213.8305</td>
<td>18 - 43</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Mixed-dry/Hot-dry</td>
<td>12.7</td>
<td>3,474</td>
<td>44.1198</td>
<td>24 - 42</td>
<td>29 – 52</td>
</tr>
<tr>
<td>4</td>
<td>Hot-humid</td>
<td>22.8</td>
<td>6,756</td>
<td>154.0368</td>
<td>30 - 36</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Marine</td>
<td>6.7</td>
<td>3,853</td>
<td>25.8151</td>
<td>22 - 27</td>
<td></td>
</tr>
</tbody>
</table>

4.3.2 Result Analysis

Results of simulating the proposed turbine quantities using the aforementioned program are displayed in Figs. 4.2-4.11. Each plot demonstrates estimated wind power generation spanning the CF range derived for each case in increments of 0.1%; hence the Case 1 onshore scenario simulates 221 CF iterations between 22% and 44%. The aggregate number of turbines is represented in the grey shaded plot while the orange line represents estimated power production for a system of the corresponding size. The dotted line represents the total residential HVAC load being targeted for the given region. The program simulates a multitude of iterations with respect to given CF values. The sporadic deviations of power production, especially when viewing the
onshore scenarios, is the result of the program determining when a certain number of turbines needs to be added with each change in CF.

Figure 4.2: Case 1: Very cold/Cold power production – *Onshore*.

Figure 4.3: Case 1: Very cold/Cold power production – *Offshore*.
Figure 4.4: Case 2: Mixed-humid power production – *Onshore*.

Figure 4.5: Case 2: Mixed-humid power production – *Offshore*.
Figure 4.6: Case 3: Mixed-dry/Hot-dry power production – Onshore.

Figure 4.7: Case 3: Mixed-dry/Hot-dry power production – Offshore.
Figure 4.8: Case 4: Hot-humid power production – *Onshore*.

Figure 4.9: Case 4: Hot-humid power production – *Offshore*. 
One common attribute shared amongst the entirety of the plots is found in the behavior of the estimated power production. When compared to the target load, the generation of each system is never shown to fall below the average residential HVAC load. This is due to the program...
determining when turbines need to be added or subtracted in order to effectively meet the demand of the target load. Fig. 4.6 demonstrates this well, as the program suggests that an increase in as little as 0.1% average, annual CF can result in a reduction of anywhere from 15 to 43 turbines. The same plot also demonstrates the effects of CF value, as the spread in production potential increases with the increasing CF. As anticipated, the application of offshore wind turbines is expected to yield significantly less turbines than its onshore counterpart as a result of the much higher capacity capabilities of offshore application. A more specific example of this can be found when observing a CF of 40% in both onshore and offshore scenarios of Case 1 (Fig. 4.2 and Fig. 4.3). Onshore is projected to require approximately 25,920 V100, 2.0 MW turbines in order to account for the target load when referencing the target CF, while the equivalent CF offshore approximates 3,988 Haliade-X, 13 MW turbines instead. Moreover, the higher potential CF of offshore wind farms is estimated to reach much higher than that of onshore wind. When calculated at the theoretical maximum as estimated by the IEA, the same offshore scenario expressed for Case 1 at a CF of 52% approximates the need for only 3,068 Haliade-X turbines to account for the entirety of the region’s residential HVAC load. Table 4.2 contains condensed simulation results for each test case.

**Table 4.2: Comparison of Simulation Results Between Test Cases**

<table>
<thead>
<tr>
<th>Case</th>
<th>Climate Region</th>
<th>Onshore turbine range</th>
<th>Offshore turbine range</th>
<th>Estimated % of total household load removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very cold/Cold</td>
<td>23564 - 47127</td>
<td>3068 - 5501</td>
<td>47.98</td>
</tr>
<tr>
<td>2</td>
<td>Mixed-humid</td>
<td>28384 - 67806</td>
<td>3611 - 6475</td>
<td>51.90</td>
</tr>
<tr>
<td>3</td>
<td>Mixed-dry/Hot-dry</td>
<td>5996 - 10493</td>
<td>746 - 1336</td>
<td>45.48</td>
</tr>
<tr>
<td>4</td>
<td>Hot-humid</td>
<td>24423 - 29307</td>
<td>2602 - 4665</td>
<td>48.97</td>
</tr>
<tr>
<td>5</td>
<td>Marine</td>
<td>5458 - 6698</td>
<td>436 - 782</td>
<td>40.16</td>
</tr>
</tbody>
</table>
Upon calculating average production across all systems, it is approximated that the resulting load shed amounts to an average potential of 47% of total household load across all climate regions. Of the five climate regions tested, the mixed-humid climate region is expected to have the highest potential for load reduction with an approximated 51.90%. Alternatively, the marine climate region is projected to experience the lowest potential for household load removal at 40.16%. Further analysis of the data in Table 4.2 yields interesting results when comparing onshore and offshore application. Although the rated power of the offshore turbine being considered is 6.5 times larger than the onshore turbine, calculations suggest that onshore scenarios require approximately 8.6 times as many turbines as the offshore counterpart on average. This is significant because it helps to display the effectiveness of the higher CF potential inherent of offshore wind application.

4.4 Summary

This Chapter-4 presented a technical approach for targeting residential HVAC load using an onshore and offshore wind turbine case study. An evaluation program was developed that determined 10 sets of wind turbine ranges across the five case studies being observed. Resulting analysis of this data demonstrated an abundance of effective load shedding probabilities while also demonstrating the major differences in turbine quantities when comparing offshore to onshore scenarios. Both scenarios resulted in evaluating the potential total percentage of household load removal averaging at approximately 47% across all U.S. households.²

Chapter 5: Conclusions and Recommendations for Future Work

5.1 Introduction

Chapter 5 concludes the major findings and contribution in developing grid connected renewable energy systems for residential load management. This chapter also provides concepts and recommendations for potential future work.

5.2 Summary and Conclusions

This thesis analyzed the potential effectiveness of a proposed methodology for targeting residential HVAC loads across the entirety of the continental U.S. via five predetermined climate regions. The methods proposed in this series of work applied datasets acquired from the U.S. DOE, EIA, IEA and NREL as well as associated affecting parameters into simulation functions produced using MATLAB software to develop and model systems using DER technology. The resulting systems were then simulated and observed to determine the total potential load curtailment brought upon by their annual power production.

- Chapter 1 presented a summary of the background, motivation, and endeavors for developing the techniques proposed in this body of work as well as the main goals and limitations associated.
- Chapter 2 presented an in-depth literature review pertaining to various studies of DER integration for targeting various load formats. This included works regarding performance assessment, project development and other novel methodology being promoted in association with the application of wind and solar technologies.
- Chapter 3 presented a concept for targeting residential HVAC loads using PV panels and solar radiation as the most affecting parameter. The resulting systems were estimated to alleviate anywhere from 40.15% to 55.83% of total household load depending on the
climate region being observed. The chapter also provided insight on the effectiveness of PV panels as a whole in areas of varying solar radiation and the relationship each climate has with household electricity loads.

- Chapter 4 presented a concept for targeting residential HVAC loads using both onshore and offshore wind turbines and using capacity factor data as its most affecting parameter. The resulting aggregate systems were estimated to alleviate the equivalent of anywhere from 40.16% to 51.90% of total household loads depending on the climate region being observed. This chapter also provided insight on comparing onshore and offshore applications when being used to target a similar load as well as the effects capacity factors have on total annual power production.

Both the PV approach and the wind energy approach provided substantial potential for alleviating the load caused by residential HVAC and thus provide an effective load shedding potential for reducing grid stress. These concepts also provide both utility operators and researchers with new systems in the study of DERs and demand response opportunities. Ultimately, both techniques provide a means for alleviating increasing load demand without causing end-users to adopt new lifestyles or change their habits when it comes to their space conditioning practices.

5.3 Recommendations for Future Work

Future work on these topics may include particular focus on different housing types aside from the benchmark residential home as well as improving recordable load data through observing more unique and specific test cases to improve accuracy. This includes community-based housing such as apartment complexes and townhome structures. Furthermore, while these particular case studies focused on base-level load data, additional studies may aim to include both high- and low-
level loads provided by DOE datasets as well to provide a more comprehensive outlook. Alternatively, future studies may seek to analyze the economic feasibility of installing both PV and wind turbine generation systems in order to target loads drawn from residential HVAC components. While the technical analysis resulted in attractive load shedding opportunities, the cost-effectiveness of the proposed methodology still requires analysis to determine true feasibility. Fortunately, with prices in solar PV and turbine technology continuing to lower as performance advances, the reality of affordable renewable energy production continues to become more viable, thus allowing more opportunities to arise. The prospect of partial load targeting in general may also be further explored in other areas outside of residential housing, as well. Supplementing industrial, commercial, and residential power in areas of high-peak demand can still provide substantial support in reducing strain on utility services without requiring significantly larger energy generation sources.

5.4 Contributions

In contrast to the existing literature, the major contributions of this thesis are as follows:

- An efficient and novel approach at addressing, specifically the load brought upon by HVAC usage in the residential sector;
- A comprehensive method of observing both solar and wind energy-based major attributing factors based on DOE climate regions across the entirety of the continental U.S.;
- Effective concept for providing significant load shedding opportunity without effecting end-user quality of life.

Snippets of MATLAB codes developed for this body of work are provided in Appendices I through III.
References


Appendix I:

MATLAB snippet of code for PV System Development

This code snippet was written and commented by Oscar Samuel Acosta using MATLAB software and used to develop the data and plots provided in Chapter 3. This snippet presents lines specific to the Case 1: Very cold/Cold climate regions including initial parameters and calculations for determining arrays for PV - raw power requirement, panel number, and estimated annual power generation. The equivalent procedures are carried out for all five climate regions with their corresponding parameters.

```matlab
% Case 1    Very cold/Cold
E_Total_annual_1  = 8913;
E_annual_1  = 4274;
E_daily_1   = E_annual_1/365;
Irr_1       = 4.00 : 0.01 : 5.25;

%Case 1 Calculations - Very cold/Cold
nm1 = length(Irr_1);
for i=1:1:nm1
    Psize_1(i) = (E_daily_1 / (Irr_1(i) * PR_PTC));
    Panels1(i) = ceil(Psize_1(i)/W_panel);
end

Preal_1 = Panels1*(W_panel*1000);
Pgen_1 = Irr_1.* Preal_1 * PR_PTC * 365;
```
Appendix II:

MATLAB snippet of code for Onshore System Development

This code snippet was written and commented by Oscar Samuel Acosta using MATLAB software and used to develop the data and plots provided in Chapter 4. This snippet presents lines specific to the Case 1: Very cold/Cold climate regions using onshore wind energy including initial parameters and calculations for determining arrays specific to onshore wind - total power requirement, turbine number, and estimated annual power generation. The equivalent procedures are carried out for all five climate regions with their corresponding parameters.

```matlab
% Case 1 Very cold/Cold
E_annual_1 = 4274;
AnnualTotals1 = E_annual_1 * 1000 * 42500000;
onshore_capfac1 = .22 : 0.001 : .44;

% Case 1 Calculations - Very cold/Cold
nm1 = length(onshore_capfac1);
for i=1:1:nm1
    Psize_1(i) = AnnualTotals1 / (onshore_capfac1(i) * 8760);
    Turbines1(i) = ceil(Psize_1(i)/Cap_Turbine_ons);
end

Preal_1 = Turbines1*Cap_Turbine_ons;
Pgen_1 = onshore_capfac1.* Preal_1 * 8760;
```
Appendix III:

MATLAB snippet of code for Offshore System Development

This code snippet was written and commented by Oscar Samuel Acosta using MATLAB software and used to develop the data and plots provided in Chapter 4. This snippet presents lines specific to the Case 1: Very cold/Cold climate regions using offshore wind energy including initial parameters and calculations for determining arrays specific to offshore wind - total power requirement, turbine number, and estimated annual power generation. The equivalent procedures are carried out for all five climate regions with their corresponding parameters.

```matlab
% Case 1 Very cold/Cold
E_annual_1 = 4274;
AnnualTotals1 = E_annual_1 * 1000 * 42500000;

% Case 1 Calculations - Very cold/Cold
nm1 = length(offshore_capfac);
for i=1:1:nm1
    Psize_1(i) = AnnualTotals1 / (offshore_capfac(i) * 8760);
    Turbines1(i) = ceil(Psize_1(i)/Cap_Turbine_offs);
end

Preal_1 = Turbines1*Cap_Turbine_offs;
Pgen_1 = offshore_capfac.* Preal_1 * 8760;
```
Appendix IV:

List of Publications

List of publications that were generated during my MSEE studies at UTEP are listed below.

**Peer-reviewed Conference Papers**

*: my graduate advisor and corresponding author of the paper


**Abstract/Poster (at 2022 IEEE PES General Meeting)**


**Peer-reviewed Journal Paper Under Review**

Oscar Samuel Acosta was born in El Paso, Texas. He received his Bachelor of Science in Electrical Engineering from the University of Texas at El Paso in the year 2020. In August of 2020, he began pursuing his Master of Science degree in Electrical Engineering (M.S.E.E). In August of 2021, he joined the Power & Renewable Energy Systems (PRES) Lab within the UTEP ECE department and began research under the direct supervision of his thesis advisor and PRES Lab director Dr. Paras Mandal who provided guidance and mentoring throughout his thesis in the area of Electric Power and Renewable Energy Systems, in particular, renewable energy sources (solar, onshore wind, and offshore wind) - integrated power grid, and energy management system. During this period, he gained a Graduate Certification in Electrical Power and Energy Systems from ECE, UTEP as well as developed his skills in advanced research and publication practices for international research conferences. His research has been accepted for publication at the 2022 IEEE Power & Energy Society General Meeting and he was awarded funding from the National Science Foundation and Department of Energy for continued research in the fields of renewable and electrical power engineering. Mr. Acosta is a Graduate Student Member of IEEE and is expected to continue his education by pursuing a Ph.D. degree at UTEP under the supervision of Dr. Paras Mandal and working with the PRES lab.

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This thesis was typed by Oscar Samuel Acosta.