Design Optimization for Net Zero Energy Apartment Buildings in Lebanon: A Parametric Performance Analysis

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Imagine a structure that is resilient, self-sufficient, and sustainable. Envision a building that generates its own energy and electricity. A space that is comfortable, healthy, and inviting. A space where you are never too hot or cold. The temperature and humidity are just right. Daylight is ample without unwanted heat and glare. A space where the warm gentle spring breezes flow through it eloquently. Imagine a house where you're never worried about power outages, uncomfortable indoor conditions, and energy cost. *Enter your new Zero Energy Home*, an oasis of never-ending possibilities and dreams!

Abstract

Buildings have a significant impact on energy use and the environment, accounting for approximately 20% of global energy consumption and 40% of CO_2 emissions. The US Energy Information Administration predicts that rising living standards and populations in non-OECD nations, including Lebanon, will inevitably lead to a significant hike in electricity demand, leading to a 50% rise in global energy consumption and exacerbating climate change. However, realizing energy efficiency in residential buildings remains a significant challenge for many countries such as Lebanon due to non-existent legislative frameworks and absence of green construction practices. As a result, energy consumption in Lebanon is a significant source of economic distress, social inequity, and air pollution. Approximately half of the Lebanese electric generation is consumed by the residential building market. Despite this, energy conservation measures (ECMs) have not been widely adopted in standard Lebanese apartment buildings, the most prevalent archetype of housing in the nation.

This dissertation evaluated the feasibility and applicability of Net Zero Energy apartment buildings (NZEB) in Lebanon's residential sector. To address these issues, 1,110 individuals in the US and Lebanon were surveyed to gain a deeper understanding of the perceptions and potential of NZEBs in Lebanon. Additionally, the dissertation examined the effects of various passive and active ECMs on energy consumption in a baseline multi-family apartment building, utilizing an incremental multi-stage iterative building performance modeling and simulation approach. Simulation results identified the following variables as the most optimal energy indicators: insulated envelope, high-efficiency HVAC & DHW systems, high- performance glazing, high-efficiency lighting and equipment, and a compact square footprint. These combined variables yielded a 56% reduction in energy use over the baseline. Thereafter, building optimization yielded a NZEB with PV integration. Accordingly, the dissertation generated targeted architectural guidelines toward energy optimization for NZEB in Lebanon, encompassing passive and active design strategies. The guidelines were validated via survey responses from 152 Lebanese respondents. Finally, the dissertation provided a framework for an informational NZEB mobile based app to provide Lebanese homeowners, students, and building professionals with design guidelines to achieve NZEB in Lebanon.

Adopting a NZEB approach offers households resiliency, autonomy, and improved financial stability. They also offer robust options for improving environmental justice, social equity, and economic stability. The dissertation promotes sustainable residential building practices to reduce energy use, mitigate air pollution, combat climate change, and eliminate energy inequities. The fundamental premise of the dissertation is providing Lebanese people a viable path towards eliminating energy poverty, providing social inequity, and reducing financial strain. The dissertation aims to equip Lebanese households with Resiliency and Immunity from potential future crises. The dissertation findings clearly show that NZEB are feasible as a new design and construction paradigm within Lebanon's multi-family sector and that transitioning the existing residential market into Net Zero Energy is now within reach.

App Framework: https://5153418.igen.app
Website Framework: https://naimjabbour.wixsite.com/lebanon-NZEB

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Definitions of Terms

ACH – air changes per hour

AEC – architecture, engineering, construction

AFUE - annual fuel utilization efficiency: a measure of a gas furnace's efficiency

BEopt - Building Optimization Tool

Btu – British thermal unit

COP – coefficient of performance

CUI – carbon use intensity

DHW – domestic hot water

DOE – Department of Energy

EC – embodied carbon

ECM – energy conservation measures

EER – energy efficiency ratio: efficiency rating of air conditioners

EIA – Energy Information Administration

EPA – Environmental Protection Agency

EUI - energy use intensity: annual amount of energy used by a building per square foot

FAR – floor area ratio

HVAC – heating, ventilation, and air conditioning

IECC - International Energy Conservation Code

KWh – kilowatt-hour

LCA – life cycle assessment

LEED – Leadership in Energy and Environment

NCMA – National Concrete Masonry Association

NREL – National Renewable Energy Laboratory

NZE – Net Zero Energy

OECD - Organization for Economic Co-operation and Development

RECS – residential energy consumption survey

SHGC – solar heat gain coefficient

SC – solar Coefficient

TVIS – visible transmittance

NZEB – Net Zero Energy Building

nZEB – nearly Zero Energy Building

ZEHs - Zero Energy Homes

WWR – window to wall ratio

Executive Summary

Buildings have a significant impact on energy use and the environment, accounting for approximately 20% of global energy consumption in 2018 and around 40% of CO^2 emissions. These global trends are driven primarily by increasing electricity demand in residential and commercial buildings. Buildings are a major contributor to greenhouse gas emissions. The U.S. Energy Information Administration (EIA) predicts that rising living standards and populations in non-OECD nations, including Lebanon, will inevitably lead to a significant hike in electricity demand globally. To that end, the EIA's 2019 International Energy Outlook projected an average 2% per year or more in global energy consumption growth in buildings from 2018 to 2050 in non-OECD countries compared to 1.3% per year in OECD countries, a rate of growth five times higher. EIA anticipates that total building electricity consumption in non-OECD countries will exceed that in OECD countries in the early 2020s. By 2050, buildings in non-OECD nations will collectively consume twice as much electricity than buildings in OECD countries. As a result, the EIA predicts that world energy consumption will rise nearly 50% by 2050, primarily driven by growing energy demand in non-OECD countries, hence exacerbating climate change. Alternatively, the International Energy Agency (IEA) confirms that energy conservation and efficiency measures in buildings are major drivers in climate change mitigation efforts. However, realizing energy efficiency in residential buildings remains a significant challenge for many countries such as Lebanon due to non-existent legislative frameworks and absence of green construction practices. It's therefore imperative that homeowners, students, building professionals, and all other concerned parties be empowered to take action toward energy efficient housing.

Lebanon is currently undergoing 3 major crises simultaneously, a political crisis, economic collapse, and social unrest. The nation is also experiencing a severe gas shortage leading to chronic power outages. As a result, people have no access to reliable electricity most hours of the day. The World Bank identified Lebanon's current crisis among the world's worst since the 1850s. Furthermore, energy use and associated air pollution in Lebanon persist as a significant issue to citizens and has become a major source of concern to public health and wellbeing. The World Health Organization (WHO) estimated the percentage of air pollution in Lebanon exceeded all international standards. It's also projected that a 100% of the population is exposed to pollution levels above the WHO guidelines. To that end, the Lebanese building sector is a major consumer of energy and one of the primary drivers of air pollution in the country. The building industry consumes anywhere between 45% at the low end and 75% at the high end of total electrical demand, most of which is generated in antiquated power plants utilizing petroleum fuel oil as the main source. Energy generation accounts for a significant percentage of air pollutant emissions in the country. About half of the electricity generated is distributed to and consumed by the residential market. Consequently, the residential sector is a major contributor to air pollution, accounting for approximately 30-45% of total energy end-use consumption in Lebanon and associated emissions. Moreover, apartments constituted 67% of Lebanese households and 82% of all construction permits. Nonetheless, energy conservation and efficiency measures (ECM) have not been widely adopted due to weak legislative policies and frameworks, lack of enforcement mechanisms, absence of green construction legislation, subsidies of energy prices, and the absence of a national energy strategy. Furthermore, existing research targeting energy performance in Lebanese apartment buildings is somewhat deficient.

Moreover, Net Zero Energy building research within the Lebanese residential sector is very limited. To that end, this dissertation evaluated the feasibility and applicability of Net Zero Energy apartment buildings (NZEB) in Lebanon's residential sector. To address these issues, 1,110 individuals in the US and Lebanon were surveyed to gain a deeper understanding of the perceptions and potential of NZEBs in Lebanon. Additionally, the dissertation examined the effects of various passive and active ECMs on energy consumption in a baseline multi-family apartment building, utilizing an incremental multi-stage iterative building performance modeling and simulation approach. The main objective of this research was to develop and generate optimal architectural guidelines for the design of high-performance Net Zero Energy (NZEB) apartment buildings in Lebanon, to reduce the impacts of energy use and associated emissions as well as provide Lebanese households resiliency and autonomy. Utilizing a holistic approach, this thesis examined and investigated the interaction and impacts of multiple building variables on energy consumption in a standard Lebanese multi-family apartment building, in the context of a net zero approach.

The thesis tested the following primary hypothesis:

> *Hypothesis:* certain permutations of building variables will yield significant improvements in energy performance (5% minimum below baseline). As such, these sets of building variables should be adopted as best practice optimal guidelines for the design of High-Performance Net Zero Energy apartment buildings in Lebanon (NZEB).

To address the research hypothesis, the following primary question was investigated:

> *Research Question:* What specific permutations of Architectural Design configurations + Building Systems variables would yield the most optimal energy performance in the context of a building's overall annual energy consumption, measured using the EUI index as the primary dependent variable?

The thesis methodology employed both a qualitative and quantitative approach. The qualitative approach employed technical data collection, perception surveys, and policy reviews. The quantitative approach utilized an iterative building performance modeling and simulation analysis to examine the relationship between architectural variables and energy use in a standard Lebanese apartment building. The following sequential methodology was employed: first, a comprehensive review and examination of regulatory barriers and technical data was conducted; second, data from surveys were collected and analyzed to gauge respondents` perceptions of energy efficiency and NZEB practices; third, an extensive quantitative iterative parametric energy modeling and simulation approach was employed to assess and analyze various building performance metrics. Lastly, comprehensive optimal NZEB guidelines for apartment buildings were recommended based on simulation findings. A baseline was established for residential energy use in Lebanon, followed by an assessment of various design configurations and building system upgrades. Energy Use Intensity (EUI) was employed as the primary energy performance indicator. The Cove Tool was used as the primary energy simulation platform to evaluate and determine the most optimal combinations of ECM. To that end the study utilized an incremental multi-stage modeling approach that aimed to reduce energy loads by more than 50% before deploying on-site energy generation. Individual design configurations and buildings system variables, including passive and active strategies, were evaluated in the first modeling stage, followed by a building optimization stage examining a combination of optimal strategies (passive + active + design) derived from the first stage. Lastly, NZEB modeling optimization, including on-site renewable energy generation, was initiated to evaluate the impact on building performance.

Simulation results showed the following variables as the most optimal energy indicators: insulated envelope, high-efficiency HVAC & DHW systems, high-performance glazing, high-efficiency lighting and equipment, compact footprint, and south-facing shading systems. These variables, combined, yielded more than a 50% reduction in energy use over the modeled baseline and 32% below the 2030 baseline. Thereafter, simulation results from the NZEB Photovoltaic optimization run produced a net EUI of 0 kWh/m²/yr, a 100% reduction from the baseline. The Final EUI of 0 kWh/m²/yr, offset by PV production, paved the way to a NZEB status. Furthermore, the NZEB optimization simulation results produced an EUI 100% below the 2030 baseline threshold and the 2030 Net Zero target metric of 25 kWh/m²/yr. Furthermore, the simulation results of the NZEB optimization revealed a 100% reduction in CO_2 emissions from the baseline, reducing the building's overall carbon footprint significantly. The research adopted the following architectural variables as best-practice guidelines for the design of high-performance NZE apartment buildings in Lebanon: passive strategies-thermally insulated envelope, compact footprint, high-performance glazing, natural ventilation for cooling, passive solar for heating, shading, and daylighting; active strategies-high performance HVAC, solar DHW, and high-efficiency lighting, and energy efficient equipment.

The main hypothesis was confirmed by the following primary key findings:

- Collectively, building system optimization upgrades yielded a 56% reduction in energy consumption over the modeled baseline.
- Building NZE optimization (PV integration) yielded 100% reduction in energy consumption over the baseline (Net EUI of 0 kWh/m²/yr), a 100% reduction in CO_2 emissions at 0 Tonne CO_2e/yr, and an 100% reduction in life cycle operating carbon use intensity over the baseline.

This study is of value to a multitude of stakeholders including homeowners, architects, developers, and policy makers, as it further enhances understanding of energy impacts associated with various architectural variables. The research could have far-reaching significance impacting many areas including building codes, building science, building construction, architectural practices, energy modeling, policy, and advocacy. Findings from this study have potentially substantial implications for the advancement of building design and construction practices. Moreover, the study is likely to spur further research examining the nexus between building design and energy consumption/efficiency. The application of these findings provides the residential building industry a comprehensive roadmap to enact robust sustainable, economical, and resilient building practices. Given the state of energy production in Lebanon and the lack of reliable power supply, coupled with uncomfortable indoor environments, a NZEB approach offers households resiliency, independence, and autonomy. Furthermore, NZEB significantly lessens the financial burden of Lebanese households. NZEB Homes offer a robust path towards achieving environmental justice, social equity, and economic stability. Ultimately, the research aims to promote sustainable residential building practices to reduce energy use and waste, lessen GHG emissions, mitigate air pollution, combat climate change, and most importantly overcome energy poverty. The research's main objective is to promote a more resilient, comfortable, and healthier built environment by employing comprehensive NZEB guidelines to affect new sustainable residential building paradigms and practices. The fundamental premise of the research is providing Lebanese people a bottom-up approach and path towards resiliency and immunity from potential and inevitable future crises.

Chapter 1: Introduction

Buildings have substantial impacts on energy consumption, the environment, and overall comfort and well-being of occupants. Rapidly increasing energy use associated with residential structures is a significant and growing problem. Residential energy consumption is steadily rising and negatively impacting energy efficiency and overall greenhouse gas emissions (EIA, 2017). Air pollution in Lebanon persists as a major concern to citizens and have become a major source of concern to public health. Air pollution poses a severe threat to its inhabitants and overall environment. The World Health Organization (WHO) estimated the percentage of air pollution in Lebanon exceeded all international standards. It's also estimated that a 100% of the population is exposed to pollution levels above the WHO guidelines. In 2019, health officials indicated the number of cancer patients in Lebanon has increased by threefold in the past 15 years due to air pollution (Ministry of Public Health, 2012). These findings are reinforced by World Health Organization 2018 estimates, that over 17,000 new cancer cases were discovered and attributed to air pollution in Lebanon. To that end, the Lebanese building sector is a major consumer of energy and one of the primary drivers of air pollution in the country. The Lebanese building industry consumes anywhere between 45% at the low end and 75% at the high end of total electrical demand, most of which is generated in antiquated power plants utilizing petroleum fuel oil as the main source. Energy generation accounts for a significant percentage of air pollutant emissions in the country. Approximately a third of the electricity generated is distributed to and consumed by the residential market, mostly by apartment buildings. Moreover, the sector accounts for more than a third of the total energy consumption in the country, primarily fossil fuel based (Central Administration for

Statistics, 2007). In 2010, the country imported 120,000 barrels of oil per day to meet domestic needs, which accounted for over 90% of the total primary energy demand in the country (Energy Information Administration, 2010). Hence, the residential building sector is a significant driver of energy and electricity use patterns in the country. The residential sector is a major contributor to air pollution, accounting for approximately 30-45% of total energy end-use consumption in Lebanon and associated emissions.

Global average per capita energy consumption has been consistently increasing since the 1970s (International Energy Agency, 2018). As a result, energy conservation and efficiency measures (ECM) have become key factors in developing sustainable building policies to combat climate change and reduce greenhouse gas (GHG) emissions. Nonetheless, ECM have not been widely adopted in Lebanon's residential building industry. As a result, the country's residential green construction sector has lagged. A weak legislative and institutional framework, lack of enforcement mechanisms, absence of green construction legislation, subsidies of energy prices, and the absence of an enforceable national energy strategy have all contributed to a minimal adoption of energy efficiency measures and policies in the residential building sector. Most research to date has focused almost exclusively on the impact of either singular or cumulative building upgrades on energy use, often neglecting to holistically investigate the impact of targeted optimal upgrades. Similarly, there's a significant knowledge gap evaluating the impact of targeted permutations of architectural building upgrades. Moreover, there's a profound knowledge gap in zero energy apartment buildings. Collectively, research targeting energy performance in Lebanese apartment buildings is deficient. Furthermore, there are significant barriers to advancing the residential energy efficiency market leading to an

“Energy Efficiency Gap”, including financial, informational, and behavioral barriers. To address the knowledge gap, this study aims to investigate the impact of various architectural upgrades on overall performance to reduce the impacts of energy use and its associated emissions and air pollutants. Left unaddressed, the implications of population growth, rising energy prices and consumption, proliferation of modern home appliances, steadily increasing home sizes, and energy shortages could be profoundly detrimental to energy resiliency and the overall environment.

Architects, designers, builders, and homeowners have explored at varying degrees the adoption of green building features and practices into homes. To address this critical issue, many building professionals have resorted to a “fix all – upgrade all” approach, with the aim of drastically reducing energy use (Smeds, 2007). Green building features are of paramount significance to overall building energy consumption. However, it is not clear which permutations of architectural metrics are the most optimal as energy performance indicators in apartment buildings. As a result, there is still a substantial gap between energy performance and architectural building systems adoption. To date, neither building code nor industry guidelines provide a clear and robust delineation on best practices relating to optimal energy performance in Lebanese residential apartment buildings. Furthermore, there’s a significant gap both in literature and knowledge as it relates to zero energy apartment buildings.

Many uncertainties exist within the industry, specifically around the impact of residential architectural building variables---building design and building system metrics---on energy performance and efficiency. Consequently, policymakers, advocacy groups, building professionals, and the public are uninformed when it comes to issues concerning energy use and efficiency in apartment buildings. Given the significant size of this industry, there is tremendous potential to reduce energy use and associated environmental impacts. Hence, improving the energy performance of the residential building industry, by adopting robust energy performance guidelines, could potentially constitute a key factor in energy independence endeavors and climate-change mitigation efforts. Thus, it is imperative the industry undergoes a paradigm shift by addressing these issues to curtail the wasteful consumption of resources and associated environmental degradation.

Research Motivation & Significance

Lebanon is currently undergoing 3 major crises simultaneously, a political crisis, economic collapse, and social unrest. The nation is also experiencing a severe gas shortage leading to chronic power outages. As a result, people have no access to reliable electricity most hours of the day. The World Bank identified Lebanon's current crisis among the world's worst since the 1850s. To that end, Lebanon surpassed Zimbabwe for 2nd most hyperinflation in the world. Furthermore, air quality problems persist in Lebanon and has become a major source of concern to public health. Air pollution in Lebanon poses a severe threat to its inhabitants and overall environment. It's estimated that a 100% of the population is exposed to pollution levels above the WHO guidelines. The building sector is a major consumer of energy, and one of the primary drivers of air pollution and CO^2 emissions in Lebanon. The residential building sector accounts for more than 40% of total energy use in the country, which is primarily fossil fuel based and 90% imported. In 2019, health officials indicated the number of cancer patients in Lebanon has increased by threefold in the past 15 years due to air pollution. These findings are reinforced by World Health Organization 2018 estimates that over 17,000 new cancer cases were discovered and attributed to air pollution in Lebanon. Residential energy consumption is a significant driver of energy demand and pollution in Lebanon. Moreover, standard residential apartment buildings accounted for approx. 70% of the residential market in 2012. These apartment blocks are built for profit and to meet the basic standards. Most apartment blocks are tailored for low to middle income households, which further exacerbates issues of energy poverty and equity. Energy use intensity in Lebanon is relatively high when compared to EU nations with similar climate. A typical Lebanese residential apartment consumes approximately between 140 and 220 KWh/m^2/yr on average, compared to 65 KWh/m^2/yr in Cyprus. Similarly, Lebanese households consume a significantly higher amount of electricity compared to other countries in the region. Per capita residential consumption was determined to be 1727 kWh, placing Lebanon among the highest consumers of electricity in Western Europe and geographically neighboring countries (BankMed , 2014). This trend of energy consumption in a country dominated by an unstable and unreliable energy market is a major driver of economic instability in Lebanon. Particularly affected are low to middle income households, whom most apartment blocks are tailored for. The issue of energy poverty that plagues the Lebanese society is a systemic and widespread problem affecting socio-economic conditions as well health and overall wellbeing of citizens. Studies have shown that energy efficiency endeavors and efforts are key to promoting energy justice, energy equity, environmental justice, and socio-economic equity (Lewis, Hernandez, & Geronimus, 2020). Furthermore, low energy housing has been shown to provide healthier indoor environments by mitigating attributed health risks of conventional building practices. To that end, Zero Energy Homes have been shown to create healthier indoor environments by improving energy efficiency and ventilation.

Increased fresh air in a home may improve cognition, lessen illness, improve sleep patterns, and enhance overall productivity (Emerson, 2019). For example, one study showed a 100% improvement in cognitive function in green buildings with enhanced ventilation compared to conventional buildings (Allen, et al., 2016). Another study showed savings of hundreds of dollars per year in health care costs in low-income households living in energy efficient apartments. The same study documented 12% fewer asthma-related emergency room visits, a 48% decline in poor health, and a 23% reduction in poorly controlled asthma for children (E4TheFuture, 2016). Zero energy homes have been shown to provide better health and well-being to households through enhanced indoor air quality and energy efficiency. The exclusion of outdoor air pollutants via airtight building envelopes, the enhanced well-balanced fresh air ventilation system, and robust filtration systems are all essential components of a Zero Energy Home's approach to a healthier indoor environment. Besides providing a more energy efficient and healthier home, Zero Energy Homes provide homeowners a robust financial return by reducing energy bills upwards of $125-$200 per month (Zero energy project, 2020). Zero Energy Homes are an effective approach to address Lebanon's energy poverty and inequity problem, household economic instability, poor indoor air quality, increased energy consumption, air pollution, and overall health and wellbeing. Furthermore, Zero Energy Homes can play a major role in driving the climate change conversation forward. These structures constitute a necessary building block towards achieving a more sustainable and resilient society. In essence, Zero Energy Homes offer us a clear path towards achieving environmental justice, social equity, and economic stability. To that end, the research analyzed the impact of building upgrades on energy performance in a standard Lebanese apartment building to provide comprehensive guidelines to affect new sustainable residential building paradigms toward establishing a Net Zero Energy Design framework. NZE buildings are high-performance sustainable structures that generate enough renewable energy on site to meet annual energy consumption requirements. A NZE approach offers households resiliency, independence, and autonomy. Moreover, ZEBs significantly lesson the financial burden of Lebanese households as well as offer a robust path towards achieving environmental justice, social equity, and economic stability. The research aims to minimize the impact of the Lebanese residential sector on energy consumption, air pollution, and associated health impacts. The fundamental premise of the research is to provide Lebanese people a path towards resiliency and immunity from future crises.

Research Hypothesis, Questions, Specific Aims

Research Hypothesis

To address these uncertainties, gaps, and opportunities, this research explored methods to optimize energy performance in Lebanese apartment buildings. The research evaluated various permutations of architectural indicators, assessing the relationship between building upgrades and energy performance in apartment buildings. A comprehensive analysis was conducted analyzing the impact of targeted permutations of architectural variables on energy consumption in a standard Lebanese apartment building. The study examined several architectural variables to identify top energy performance indicators encompassing building design elements and building system components. The goal of this analysis was to provide a robust roadmap guiding homeowners, builders, planners, designers, and policymakers toward more sustainable building practices. The research provided comprehensive guidelines to affect new sustainable residential building paradigms & practices toward establishing a Net Zero Energy Design framework. Furthermore, the study aims to minimize the impact of the residential sector on energy use and air pollution in Lebanon.

This research was designed to examine the hypothesis that certain permutations of targeted architectural variables (Building Design & Building Systems) will yield significant improvements in energy performance (5% minimum below baseline). As such, these sets of building variables should be adopted as best practice optimal guidelines for the design of High-Performance Net Zero Energy apartment buildings in Lebanon (NZEB). The following strategies were predicted to significantly improve overall performance:

- Passive strategies: thermal mass (insulation), ventilation, shading, and daylighting.
- Active strategies: HVAC systems, solar DHW, appliances, lighting, and controls.

The following architectural indicators, encompassing design and system variables, were hypothesized to significantly reduce energy consumption (5% threshold below baseline):

- Architectural design indicators: (1) compact footprint, (2) south-facing shading systems, and (3) low percentage southern window to wall ratio.
- Architectural system indicators: (1) insulated envelope, (2) high efficiency HVAC & DHW systems, (3) high-performance glazing, and (4) high efficiency lighting.
- The most optimal architectural indicators were expected to include insulated envelope, high-efficiency HVAC & solar DHW, high-performance glazing, high-efficiency lighting and equipment, compact footprint, and south-facing shading systems.

In contrast, the following variables were not projected to heavily influence energy consumption or improve efficiency: architectural style and typology, interior layout, and roof characteristics.

Research Questions

The research asked the following primary question to assess the relationship between building upgrades and energy performance in the context of a Zero Energy Design framework: What optimal architectural upgrades/features would have the largest impact on residential energy consumption patterns in the context a standard residential housing apartment block in Lebanon? Furthermore, the following questions were also addressed to evaluate the correlation between architectural building components and energy efficiency:

- What impact would various iterations of Architectural Design variables have on energy consumption?
- What impact would various iterations of Building Systems variables have on energy consumption?
- What impact would various iterations of Architectural Design + Building Systems variables have on energy consumption?
- And lastly, what specific permutations of Architectural Design + Building Systems variables would yield the most optimal energy performance, utilizing NZE as the benchmark?

Specific Aims

To test the hypothesis, an iterative parametric computer modeling and simulation analysis was employed to comprehensively evaluate the impact of various architectural metrics on energy consumption. The study's specific aims encompassed the following steps:

1. Establishing a consistent baseline for residential energy consumption in standard residential apartment building in Lebanon.
2. Modeling/simulating parametric runs to assess the impact of various iterations of architectural design variables on annual energy consumption.
3. Modeling/simulating parametric runs to assess the impact of various iterations of building system variables on annual energy consumption.
4. Modeling/simulating parametric runs to assess the impact of the most optimal iterations of architectural variables, encompassing combinations of building design and building systems, on annual energy consumption.

Research Objectives

The research analyzed the impact of various targeted building upgrades on energy consumption in a standard Lebanese apartment block to provide comprehensive guidelines laying the foundation for a Net Zero Energy Design framework. The research aimed to generate a body of knowledge that will assist in proliferating the efforts to minimize the impact of the residential sector on energy use and associated air pollution. The objective of the research was to promote the adoption of high-performance apartment buildings that cost less to heat and cool, are more comfortable and healthier for occupants, and have a positive impact on the environment. NZE buildings offer Lebanese households independence, resiliency, safety, and autonomy. Moreover, they also significantly lesson the financial burden. Most importantly, Zero Energy Homes provide a robust path towards achieving environmental justice, social equity, and economic stability.

A direct outcome of the research yielded comprehensive performance-based guidelines for Net Zero Energy residential apartment buildings in Lebanon, encompassing both architectural design and building systems variables. To that end, energy modeling and simulation were the primary methodologies utilized to develop and generate the guidelines. Best practices for apartment buildings were compiled based on an iterative process assessing various architectural parameters and variables, including building design and systems. The sought-after guidelines provide a roadmap outlining the best and most optimal path forward to implement and adopt a Net Zero Energy framework within the Lebanese residential sector. The guidelines were meant to be performance-based in lieu of prescriptive, focusing on comprehensive passive green building strategies and active system upgrades. The research also aimed to develop a framework for an informational mobile App to inform and educate various stakeholders on Net Zero Energy best practices. The following were the main objectives of these primary set of deliverables:

- Propagate the adoption, design, and implementation of high-performance Net Zero Energy apartment buildings in Lebanon.
- Inform policy makers, advocacy groups, industry professionals, and the general public about effective residential energy consumption and efficiency strategies,
- Affect and change energy consumption patterns within Lebanon's residential sector and market,
- Mitigate and reduce the impact of residential energy consumption on air pollution in Lebanon,

- Reduce energy poverty and promote social equity,
- And lastly, increase the resiliency, independence, safety, and autonomy of Lebanese households.

Key Stakeholders

The issue of energy consumption and associated air pollution have an impact on all Lebanese citizens. To that end, the key stakeholders of this study encompass the entire population, regardless of background, classification, or location. Energy poverty, unreliability, and instability affect all sectors of the population. Increasingly, low-income and middle-class households have been impacted the most. Electricity outages and shortages have plagued and still are a significant segment of the population, especially households residing in typical apartment blocks. The research's primary stakeholders and beneficiaries encompass three main groups, citizens, building professionals, and public officials. The main constituents of the citizens category include homeowners, renters, and students. Architects, builders, contractors, and developers make up the building professionals' category. Lastly, the public officials group includes local representatives, policy makers, and elected officials.

Research Benefits

This study seeks to advance the knowledge base of energy efficient practices and strategies within the Lebanese residential sector. Its main objective is the proliferation of more sustainable, resilient, and energy positive buildings. The research aims to promote Net Zero Energy Buildings as a viable and sustainable building approach to combat energy poverty and air pollution in Lebanon. The study is anticipated to generate multiple benefits, both at the local and national levels. Locally, the research may yield key advancements in residential energy trends and patterns, including increased energy efficiency, reductions in energy consumption, bigger energy savings, added monetary savings, amplified resiliency and independence, and healthier indoor and outdoor environments. A typical Lebanese household may experience a 50% reduction in energy consumption and associated expenditures. Furthermore, the research may have far reaching and overarching benefits including the following national benefits, reductions in energy poverty and social inequity, reductions in greenhouse gas emissions, and reductions in air pollution.

Chapter 2: Background on Residential Energy Use and Patterns

Background on US Residential Energy

Buildings have a substantial impact on energy consumption and the environment. According to the Energy Information Administration (EIA), the U.S. residential building sector consumes more than half of total primary energy expenditures attributed to the building sector (Figure 1). Detached and attached single-family homes account for 69.1% of the total residential housing units (EIA, 2017). 80% of the total U.S. residential site energy is consumed by these single-family buildings (RECS, 2009). Statistically, detached single-family homes account for the largest energy consumption among all residential structures in the US (EIA, 2017). The square footage of US homes continues to increase in size than those homes built in earlier decades, a noteworthy trend as most energy end-uses (heating, cooling, lighting, hot water, etc.) are impacted by building size and footprint. Data from the 2016 Census' *Annual Characteristics of Housing* report points to a significant spike in the number of homes built in 2015 with at least 3,000 square feet (SF) of floor area, higher than any previous year. As home sizes increase, heating and cooling loads rise, lighting requirements grow, and the overall energy use surges. In 2009, estimates from the EIA's residential energy consumption survey show that space conditioning (cooling and heating) account for more than 48% of energy use in an average U.S. residence (RECS, 2009). Moreover, Department of Energy (DOE) data points to heating, water heating, lighting, and equipment end-uses as the largest drivers of residential energy demand. Collectively, these end-use energy drivers account for more than two-third of total site energy use (Figure 2). Moreover, space heating accounted for the largest end-user of residential site energy (EIA, 2017).

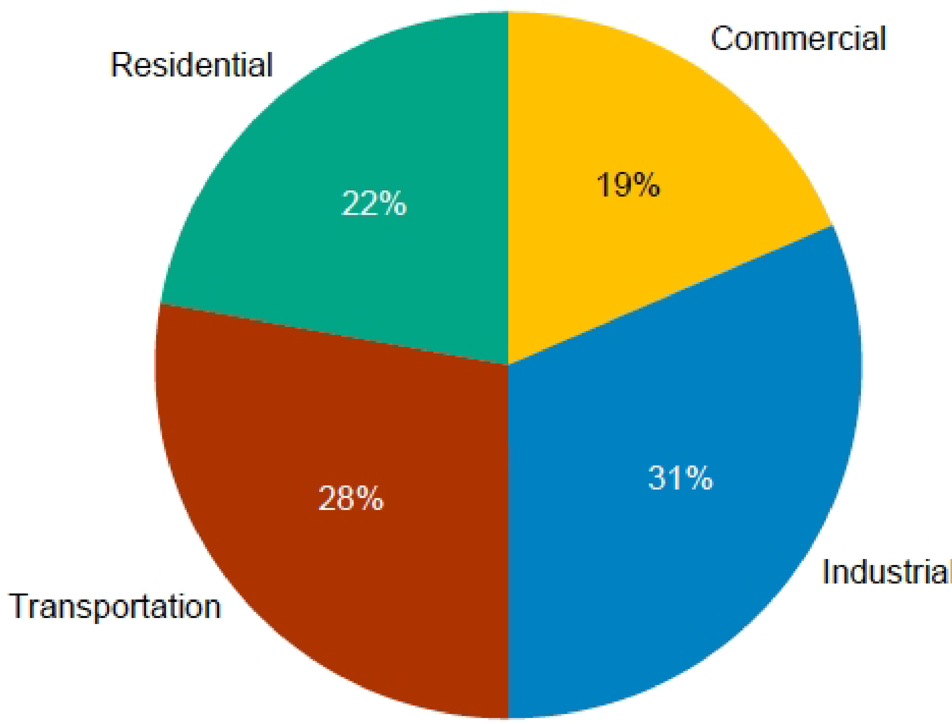

Figure 1. Breakdown of U.S. energy consumption end-uses (EIA, 2017).

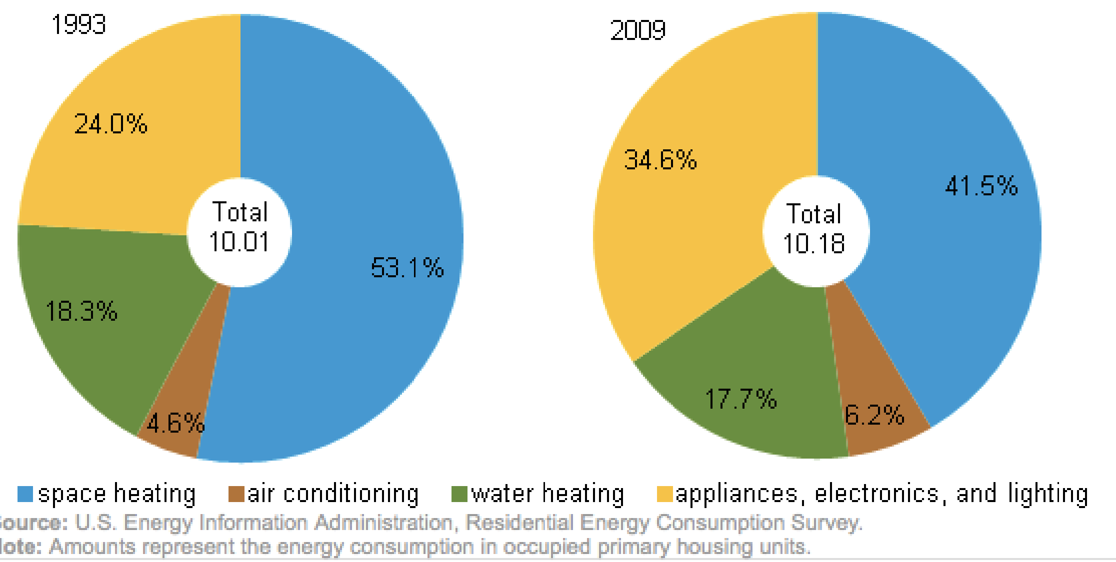

Figure 2. U.S. Home energy end-use consumption comparison (EIA, 2017).

EIA data show an increasing number of energy efficiency trends, specifically among cooling, heating, and refrigeration equipment in the U.S. (EIA, 2017). Hence, the energy consumption of these end uses has been significantly reduced compared to two decades ago. Nonetheless, these energy reductions and savings have been offset by other systems that have been incorporated into homes. Homes now contain more energy-consuming devices. The agglomeration of the such products as televisions, dishwashers, clothes washers, DVDs, DVRs, cell phones, audio-video equipment, and mobile devices, have significantly impacted the energy outlook of homes. According to the EIA, the average U.S. household consumed 10,649 kilowatt hours (kWh), an average of about 877 kWh per month in 2019, of which the largest portion was for appliances, electronics, lighting and miscellaneous uses. The average US multilevel multi-housing development has an EUI of 188 KWh/m^2/YR (59 Kbtu/SF/Year) (EIA-EnergyStar). This new paradigm of ever-expanding energy end-uses is presenting a substantial challenge to homeowners, designers, and sustainability professionals. The majority of fuel sources for that energy is derived from fossil fuels, which include coal, oil, and natural gas (DOE, 2016). As a result, U.S.

residential sector contribution to greenhouse gases emissions is significant and steadily increasing. It is imperative to explore innovative approaches to reduce energy use in homes. Furthermore, Department of Energy (2016) and World Energy Council (2016) projections have alluded to somewhat of a turbulent energy market, riddled by uncertainties and insecurities. Homeowners in the U.S. are not immune to these market fluctuations. Uncertainties in future energy prices and availability pose a serious threat to a homeowner's bottom line and overall economic well-being. It is therefore imperative to devise more energy efficient and adaptively resilient residential building models. The following section will present an overview of the efforts undertaken by the building industry and other organizations to promote more robust and efficient building energy paradigms.

Past and Current Trends in Residential Building Industry

The average U.S. household used about 77 million British thermal units (Btu) in 2015, down from 90 million Btu's in 2009 and compared with 138 million Btu's in 1978, a reduction of 31% (Figure 3). This in part is due to upgraded appliances and HVAC equipment that use less energy and reduced infiltration through walls, roofs, and windows due to improved insulation and construction techniques. Nonetheless, home energy consumption is still high relative to where it should and could be. Various efforts have been undertaken to address this problem via residential code improvement and industry initiatives (Figure 4). To address code and industry shortfalls, the DOE initiated a program in 1993 called "Building America" with the goal of reducing whole-house energy consumption for new homes by 50% by 2015 and 95% by 2025 (Anderson & Christensen, 2006). The program is a private-public partnership aiming at improving new and existing home energy performance across the U.S. In 2002, the DOE initiated the “Zero Energy Homes-ZEH” initiative, making available the latest research development concepts to homebuilders and homeowners across the United States. DOE’s objective was to help builders and homeowners construct homes that generate as much energy as they consume over the course of a year. The DOE designated various teams, working with the National Renewable Energy Laboratory (NREL), to introduce ZEH concepts into the residential market. To date, the Building America/ZEH program has been an incubator of innovations in the residential building sector, leading to significant reductions in energy use (Figure 5). According to the DOE, Building America scientists have worked directly with approximately 300 U.S. homebuilders and have improved the performance of more than 42,000 homes. In 2012, DOE recognized nearly 30 game-changing building accomplishments from the years 1995 through 2012 as “Building America Top Innovations”. However, most of the DOE efforts outlined above are voluntary in nature. As a result, as of 2017 only 10% of new homes in the U.S. are built to surpass minimum efficiency standards.

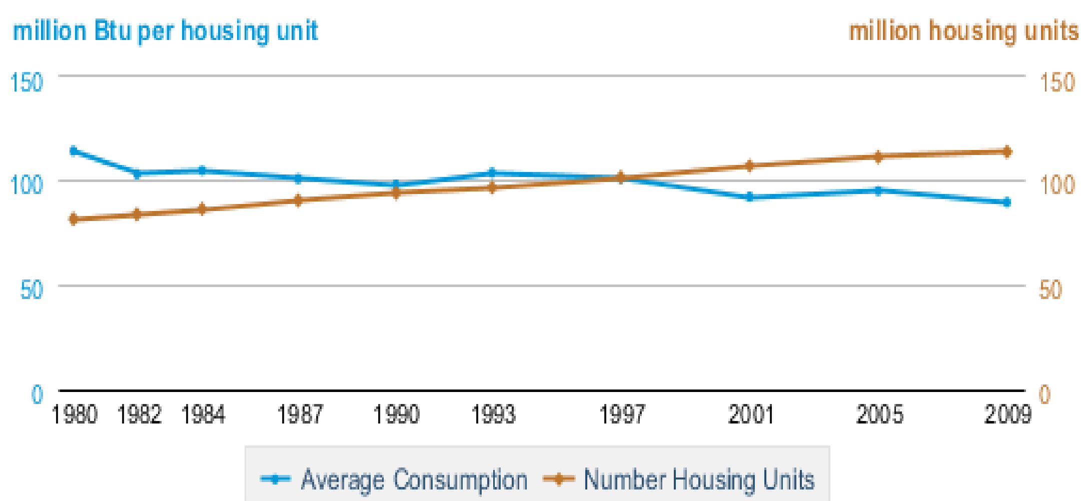

Figure 3. Average energy use per home and number of units (EIA, 2017).

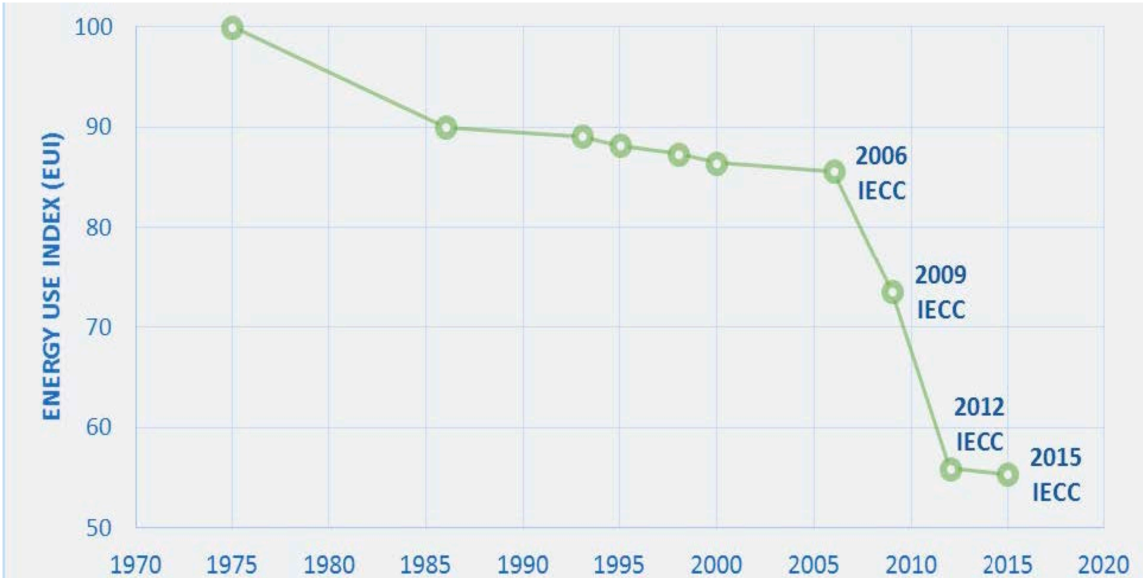

Figure 4. Residential code development from 1970 to 2015 (IECC, 2016).

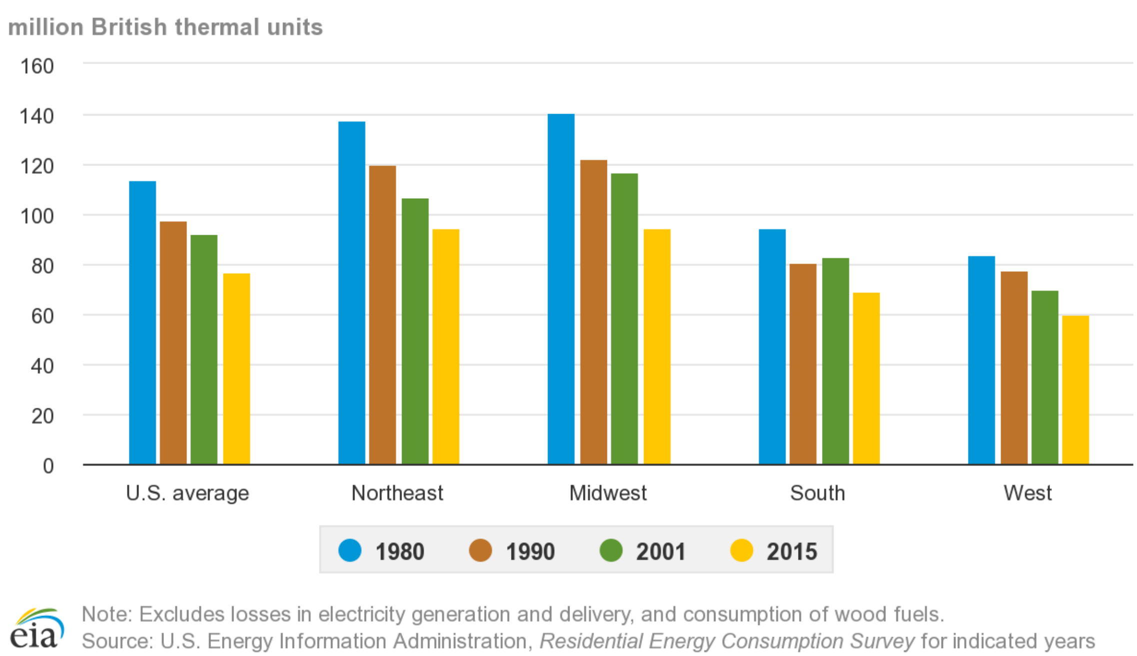

Figure 5. Energy consumption per household in the US

Transitioning to More Sustainable Building Practices

Studies have illustrated that energy conservation measures (ECM) could potentially reduce building energy consumption by 25-50% (Crawley, 2009). Research conducted by the U.S. Green Building Council have shown that green buildings tend to have energy use intensities on average of 69 kBtu/sf, 24% lower than their traditional counterparts at 91 kBut/sf. Research conducted by the DOE, NREL, and other groups have all alluded to a strong connection between building system upgrades and enhanced energy performance across industry spectrums (Crawley, 2009). For example, upgrades in insulation have been shown to yield significant reductions in heating loads (Yılmaz, 2007). Similarly, upgrades in glazing and HVAC systems have also generated substantial savings in energy consumption in residential structures in various locations (Logue, 2013). Serious efforts have been undertaken by various groups such as NAHB, DOE, EPA, NREL, EIA, USGBC, and NBI to advance the science and the overall state of the industry (Scofield, 2009). For instance, the International Energy Conservation Code has been updated to reflect a more sustainable emphasis and approach in its 2015 version. Similarly, many municipalities, cities, and states in the United States have been pursuing more performance-based building codes in an effort to transition toward more sustainable practices such as Cambridge, Portland, Santa Monica, and Austin. Nonetheless, there is still a level of uncertainty in regard to what system upgrade combinations might offer the most optimal performance (NREL, 2011). Furthermore, the relationship between building design configuration and energy performance remains ambiguous and largely untested. The transition of industry standards into sustainable building practices is well documented; however, research on the impact of targeted optimal energy indicators is still deficient.

Background on European Residential Building Policies

Worldwide residential energy consumption and demand has experienced steady growth in the past decade. Modern day necessities and standard of living expectations have yielded higher energy consumption patterns. This holds true to the Europe, where residential buildings accounted for 25-40% of total energy consumption in 2016 and 20-35% of greenhouse gas emissions (Eurostat, 2020). The ever-increasing trends of larger homes and the proliferation of electronic equipment and appliances have amplified energy and electricity demand within the Europe's residential sector. However, Europe have successfully offset these trends by adopting robust energy conservation and efficiency policies. These policy measures call for action on a global, regional, national, and local level. To that end, the European countries utilized the following measures and instruments to improve efficiency and reduce overall energy consumption: high-performance design, energy labeling, energy efficiency directives, energy performance benchmarks and metrics, targeted subsidies, educational campaigns, energy supplier obligations, and various monetary tools and incentives (European Commission, 2020). Many policies and initiatives have been implemented in the EU since the early 1990s to reduce energy use in the residential sector (Appendix A). Most policies align with the EU's energy and climate "20-20-20" targets adopted in 2007 and encompassing the following three pillars: reducing energy consumption by 20%, reducing greenhouse gas emissions by 20%, and increasing renewable energy coverage of the EU's final energy consumption to 20% (Tzeiranaki, 2019). Hence, energy efficiency has become a key driver of sustainable energy and building policy objectives in the EU. The EU adopted an Energy End-use Efficiency and Energy Services Directive (ESD) in 2008 to advance, promote, and adopt energy saving measures (European Commission, 2020). The ESD was the first directive requiring member states to adopt energy efficiency targets and benchmarks. The ESD also mandated that member states enact and adopt National Energy Efficiency Action Plans (NEEAP), outlining the specific measures and mechanisms implemented to achieve the directive goals and objectives. To further advance energy efficiency policies across the EU and various member states, the Energy Efficiency Directive (EED) was adopted in 2012, replacing the ESD. In addition to energy efficiency targets, the EED introduced binding national processes encompassing legal obligations. Furthermore, the new directive established the following energy efficient mechanisms: efficient cogeneration, mandatory energy audits, promotion of energy service, energy saving obligation schemes, metering, and consumer behavior programs (Tzeiranaki, 2019). One of the primary energy-saving instruments adopted in the EU in 2002 was the Energy Performance of Buildings Directive (EPBD) (European Commission, 2020). The directive targeted the building sector primarily focusing on both residential and non-residential structures. The directive required member states to implement measures such as energy performance certificates for rented and sold buildings. It also mandated that all new buildings must be Nearly Zero Energy Buildings (NZEBs) by December 31st, 2020. Moreover, the directive offered member states a methodology for establishing cost-optimal Minimum Energy Performance requirements (MEPs) for major renovations and new buildings. The EPBD also required member states to adopt mechanisms to improve energy efficiency of their existing national building stock (Tzeiranaki, 2019). To close the loop, the EU adopted the Ecodesign Directive introducing energy labeling and efficiency standards, to improve and enhance energy performance of residential appliances and equipment (European Commission, 2020). Cumulatively, the adopted policy measures and directives helped create an environment that drove energy consumption significantly down across Europe. The purpose of this analysis is to review, examine, and compare the various green building and energy-related policies in Europe, highlighting some of the more robust and progressive aspects of such measures, to emphasize the importance of policies in shaping a comprehensive and holistic approach to energy consumption. Furthermore, this section aims to explore policy best practices that could be transferred to the Lebanese residential building market.

EU Policies and Measures

Local, national, and regional policy initiatives are key drivers in the proliferation and implementation of progressive energy efficiency and green building measures in the EU. Robust policies and measures such as Energy Efficiency Directive, Energy Efficiency in Buildings Directive, Energy Performance of Buildings Directive, and National Energy Action Plans have all had significant impacts on energy consumption patterns across the EU. The following section will outline some of the EU's overarching policy measures and initiatives, followed by a specific focus on policies within targeted EU countries.

The Energy Efficiency Directive (EED)

The EED establishes uniform and comprehensive frameworks setting energy efficiency policies and measures in the European Union (EU), to help meet the "2020" targets (20% energy efficiency target) (Box 1). The following measures have been implemented to increase energy efficiency across the EU: consumer access to energy consumption data, smart metering (200 million), 1.5% annual decrease in national energy sales, energy efficient retrofits to a minimum of 3% of government buildings, mandatory energy efficiency certificates, energy efficiency standards and labeling (household appliances), obligation schemes for energy companies (1.5% energy savings of annual sales), national long-term building renovation strategies, and planning of National Energy Action Plans every 3 years (European Commission, 2020).

Provisions for the Household Sector in The Energy Efficiency Directive

"Building Renovation
- Member States shall establish a long-term strategy for mobilizing investment in the renovation of the national stock of residential and commercial buildings, both public and private (Article 4). This strategy shall encompass:
  - an overview of the national building stock based, as appropriate, on statistical sampling;
  - identification of cost-effective approaches to renovations relevant to the building type and climatic zone;
  - policies and measures to stimulate cost-effective deep renovations of buildings, including staged deep renovations;
  - a forward-looking perspective to guide investment decisions of individuals, the construction industry and financial institutions;
  - an evidence-based estimate of expected energy savings and wider benefits.

Households
- Member States shall ensure that information on available energy efficiency mechanisms and financial and legal frameworks is transparent and widely disseminated to all relevant market actors, such as consumers, builders, architects, engineers, environmental and energy auditors, and installers of building elements as defined in Directive 2010/31/EU (Article 17).
- Member States shall establish appropriate conditions for market operators to provide adequate and targeted information and advice to energy consumers on energy efficiency (Article 17).
- Member States shall, with the participation of stakeholders, including local and regional authorities, promote suitable information, awareness-raising and training initiatives to inform citizens of the benefits and practicalities of taking energy efficiency improvement measures (Article 17)."

Source: European Commission (ADEME, 2015)

Energy Performance in Buildings Directive (EPBD)

This directive initiated new mechanisms moving the building industry towards nearly zero energy status (nZEB). It mandated all member states require new buildings achieve nearly-zero energy status by the end of 2020. The directive also introduced cost-optimal methodologies establishing baseline requirements for both technical systems and building envelopes. Furthermore, the directive required routine inspections of heating, ventilation, and air-conditioning systems. Lastly, the directive also plans to apply nZEB standards to building renovations. The directive's objective is to promote overall energy conservation measures and improve efficiency, as well as increase the adoption of renewable energy strategies in buildings. The EPBD also required mandatory certification of all existing and new buildings via Energy Performance Certificates (EPC). The directive mandates that EPCs must be shown to prospective buyers or renters. To that end, EPCs encompass recommendations for cost effective and cost optimal enhancements of a building’s energy performance (ADEME, 2015).

Energy Labeling Directive (ELD)

The directive mandates energy labels must be clearly displayed on items for sale or rent. This is primarily intended to provide consumers with ample data to help make an educated and informed purchase. The label includes an overall rating, amount of energy consumed, and performance ratings (Figure 6). Currently, energy labels are available to many product groups including the following household items: lamps, televisions, washing machines, drying machines, refrigerators, household air conditioners, space and water heaters, and ovens (ADEME, 2015).

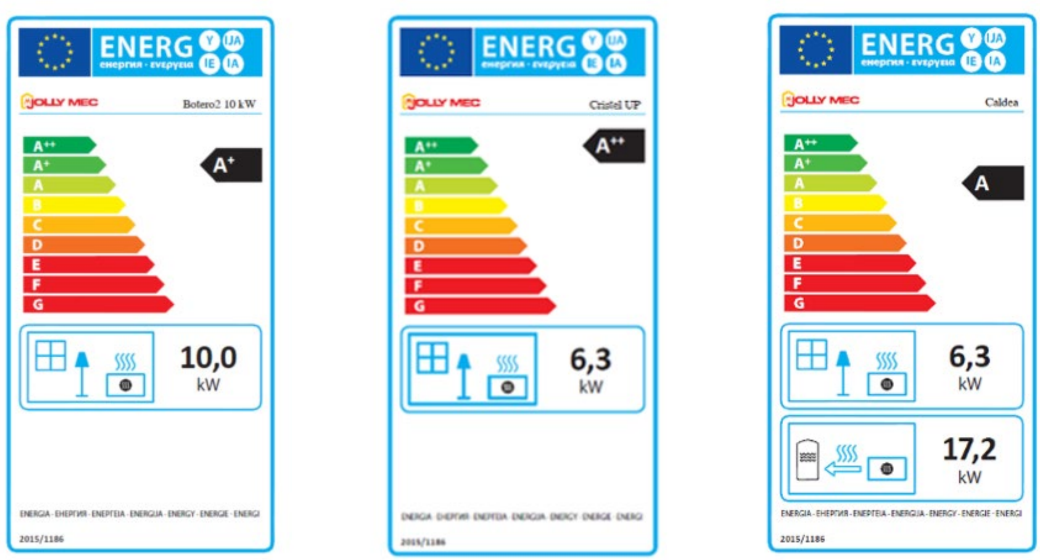

Figure 6. EU Energy label example

Eco-design Directive (EDD)

This directive establishes minimum energy efficiency standards and requirements for various products. The directive is enforced via commission regulations and voluntary arrangements with manufactures. The majority of products covered in the directive encompass household items. The following are few of the products covered by the directive: heaters, water heaters, computers, dishwashers, washers, and air conditioners (ADEME, 2015).

Minimum Levels of Energy Taxation Directive

The EU has adopted wide ranging monetary instruments including environmental taxation mechanisms to shape and change societal behavioural patterns and trends. Those taxes encompass 4 major categories: pollution, resources, transport, and energy. Energy taxation constitutes the largest portion of taxation, totaling approximately 75% of all environmental tax receipts in the EU (Eurostat, 2013). To that end, energy taxes apply to various heating fuels and electricity (Table 1). The directive also includes a 15% value added tax (VAT) on energy used by households (ADEME, 2015).

Table 1. Minimum taxation levels related to electricity and heating fuels *(ODYSSEE-MURE, 2020)*.

Fuel	Current minimum excise rates for businesses use	Current minimum excise rates for non-businesses use
Heating oil (E/1000 liters)	21	21
Heavy fuel oil (E/1000 Kg)	15	15
Kerosene (E/1000 liters)	0	0
LPG (E/1000 Kg)	0	0
Natural gas (E/GJ)	0.15	0.3
Coal & coke (E/GJ)	0.15	0.3
Electricity (E/MWh)	0.5	1.0

Renewable Energy Directive (RED)

This directive targets both large scale and small-scale renewable energy generation. It covers the energy supply industry and the end-user. The directive places a large emphasis on end-user renewable energy production to reduce fossil fuel energy consumption. Member states are also required to introduce measures into building codes and regulations, to enhance the percentage of renewable energy used in buildings. To that end, member states are mandated to include in their building codes and regulations minimum requirements of energy use sourced from renewable sources in existing and new buildings. The directive also requires member states to provide guidance for information sharing amongst various stakeholders such as architects, planners, homeowners, and builders (ADEME, 2015).

EU Household National Policy Measures

National residential building and energy policy measures have been widely adopted across the EU. The MURE and ODYSSEE databases, EU online repositories on energy efficiency policies, contain approximately 600 measures adopted in the residential sector (ODYSSEE-MURE, 2020). The policies encompass legislative, information, training, education, financial, co-operative, new market-based, and cross-cutting measures (Figure 7). Furthermore, many of the measures also focus on behavioral patterns. To that end, two behavioral typologies are identified to affect energy efficiency trends, habitual behavior (patters of space use) and investment behavior (choice of housing type). A 2009 behavioral study identified the following three factors as key drivers influencing behavioral change and adjustment: motivating factors (individual & internal), enabling factors (external constraints), and reinforcing factors (Consequences of actions) (ADEME, 2015).

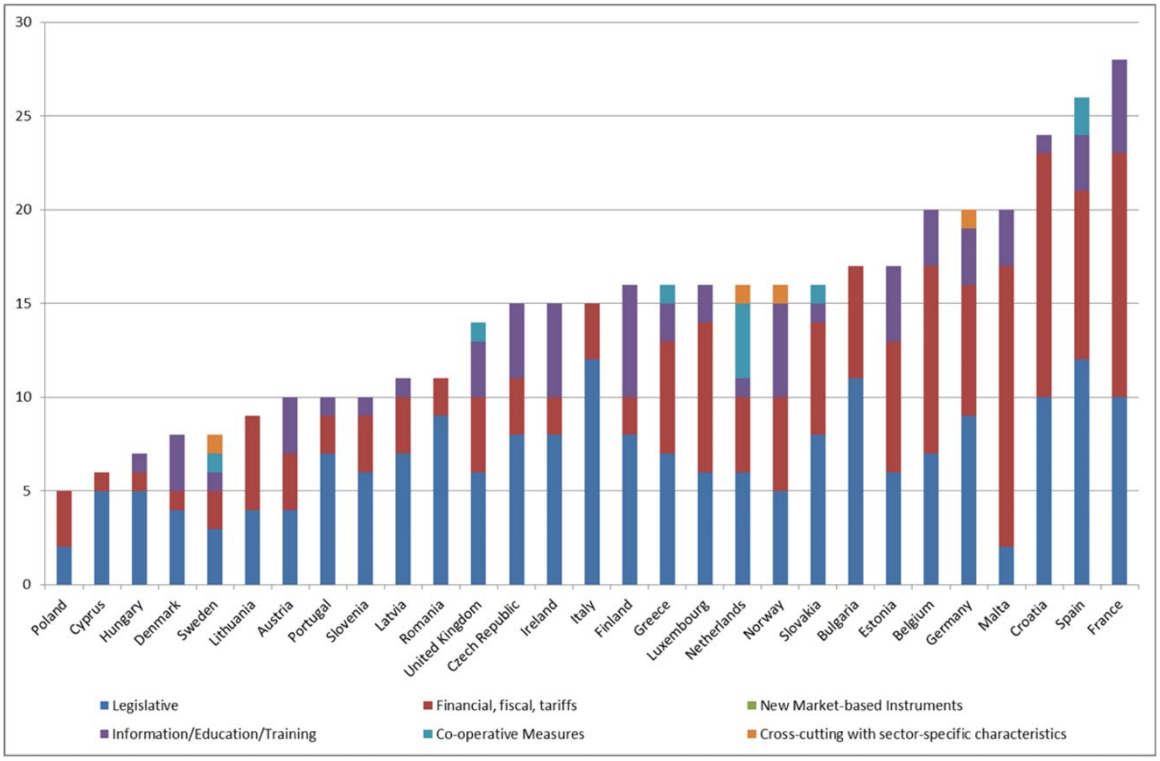

Figure 7. Number of residential policy measures by typology across the EU *(ODYSSEE-MURE, 2020)*

Country-Specific Policy Measures- Germany, France, UK

Germany adopted a National Energy Efficiency Action Plan (NEEAP) as an overarching mechanism to promote energy conservation measures. The country's policy initiatives are broken down into three main categories, energy, building, and supporting measures. Furthermore, the policies cover measures at the local, national, and regional scales (Figure 8). The country established The Energy Efficiency Fund (EEF), which consists of 23 policies and initiatives including funding structures and educational programs, to reduce overall energy use and greenhouse gas emissions. The specific policy measure calls for a 20% reduction in energy consumption by 2020 and a 50% reduction by 2050 compared to 2008 levels. It also requires a 40% reduction in GHG emissions by 2020 and an 80-95% reduction by 2050 compared to 1990 levels (ODYSSEE-MURE, 2020). Furthermore, Germany's Climate Action Program also mandates a 40% reduction in GHG emissions by 2020. On the building front, Germany initiated the Energy Efficiency Incentive Program (APEE) in 2016, providing funding for the modernization of HVAC systems in residential buildings, totaling 165 million Euros per year. An energy saving ordinance was also introduced to promote energy conservation measures. The Energy Conservation Regulation (EnEV) is a performance-based regulation mandating energy calculation to set anticipated primary energy use in residential structures (ODYSSEE-MURE, 2020). The regulation mandates an annual 20% reduction in energy use for new buildings. Moreover, Germany established two programs to promote renewable energy technologies and climate-friendly buildings: CO2 Building Rehabilitation Program and Market Incentive Program. Alongside all of the aforementioned regulations, policies, and programs, Germany provided monetary incentive to encourage residents to exceed the minimum requirement. To that end, $16.9 billion in subsidies were provided in 2009 encompassing energy efficiency and renewable energy subsidies. Similarly, 3.1 million residences were beneficiaries of monetary subsidies in the same year. The government also provided supporting measures such as educational programs, energy labeling schemes, and free access to code (ODYSSEE-MURE, 2020).

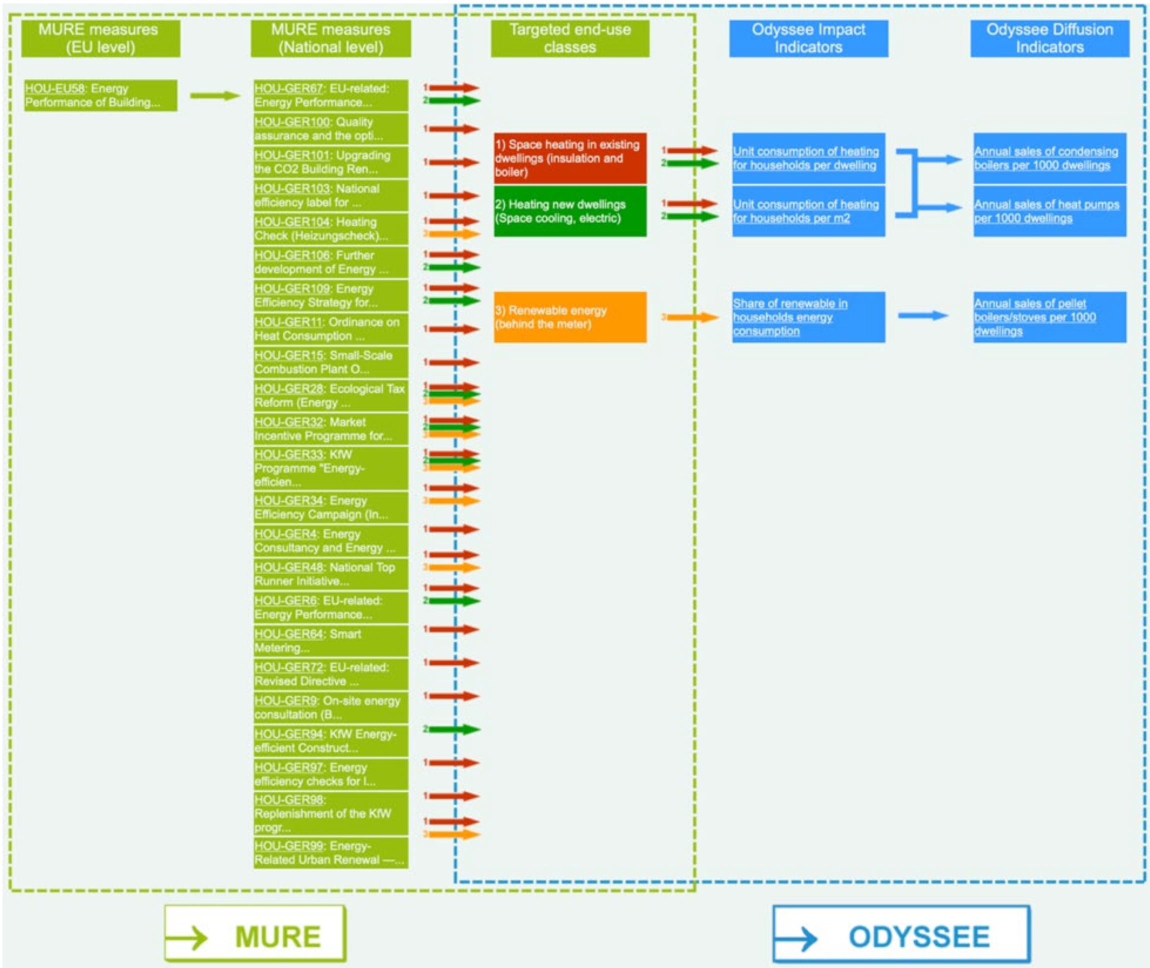

Figure 8. Policy mapper for households in Germany *(ODYSSEE-MURE, 2020)*.

France also adopted a National Energy Efficiency Action Plan (NEEAP) as an overarching mechanism to promote energy conservation measures. The plan sets a final energy consumption target of 131 Mtoe by 2020. The country's policy initiatives are broken down into three main categories: energy, building, and supporting measures. Furthermore, the policies cover initiatives at the local, national, and regional scales (Figure 9). The country introduced the Energy Saving Certificates (ESC), requiring energy providers and fuel suppliers to meet specific energy saving thresholds. A heat fund was also established as a mechanism to support the development of alternative fuels and energies such as biomass energy, geothermal energy, solar thermal, and recovery energies. France also introduced building-specific policy measures such as RT2012, which mandates all new buildings meet the nearly zero energy standard established by the EU. Furthermore, new residential buildings are mandated to establish a primary energy consumption lower than 50 KWh/m^2/year (ODYSSEE-MURE, 2020). The RT2012 further reinforces the EU's Energy Performance of Buildings Directive (EPBD), requiring buildings to be 40% more efficient than their 2005 counterparts. The RT2012 also promotes a performance-based approach to building codes and regulations. The measure targets a goal of energy positive buildings by 2020. The government also provided supporting measures including subsidies, monetary incentives, tax breaks, educational programs, energy labeling schemes, and free access to code (ODYSSEE-MURE, 2020).

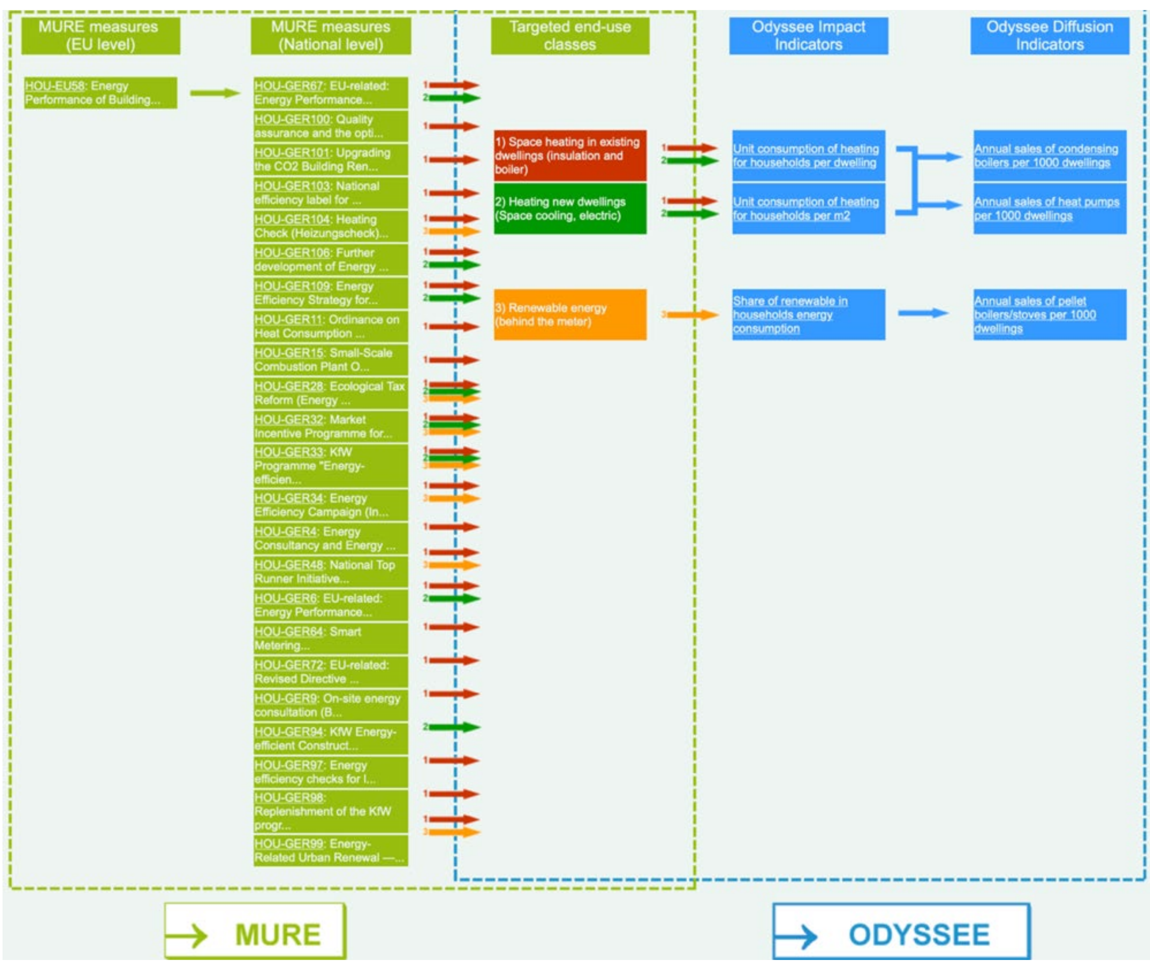

Figure 9. Policy mapper for households in France *(ODYSSEE-MURE, 2020)*.

Similarly, the United Kingdom (UK) also adopted a National Energy Efficiency Action Plan (NEEAP) as an overarching mechanism to promote energy conservation measures. The UK's policy initiatives are broken down into three main categories: energy, building, and supporting measures. Furthermore, the policies cover initiatives at the local, national, and regional scales (Figure 10). An Energy Company Obligation (ECO) was introduced to establish energy efficiency obligations. The ECO enforces lifetime carbon saving targets on large energy providers to be realized at the residential end-user. Energy Savings Opportunity Scheme (ESOS) was also established as the main instrument to enforce the EU's Article 8 of the Energy Efficiency Directive (EED). The program mandates energy audits for large enterprises. The UK's building sector was also given ample consideration via the introduction of several building regulations. To that end, L1A and L2A were established as mandatory performance-based codes, requiring energy calculation to make sure Design Emissions Rates (DER) don't exceed Target Emissions Rates (TER). The codes also address thermal envelope requirements. Furthermore, the regulations set a national benchmark for all homes to achieve zero carbon status by 2016. Moreover, the codes required new buildings to meet a minimum standard for thermal transmittance for roofs, walls, windows, and doors, as well as efficient heating systems. Smart metering and billing for households were also introduced as mechanisms to provide transparency and incentives towards energy efficiency. The government also employed monetary incentives such as tax exemptions for zero carbon homes. Feed in tariffs (FiTs) were also introduced for onsite generated electricity from small scale renewable systems. The government also initiated a Renewable heat Incentive (RIH), to promote renewable energy sources. The government also provided supporting measures including subsidies, monetary incentives, tax breaks, educational programs, energy labeling schemes, and free access to code (ODYSSEE-MURE, 2020).

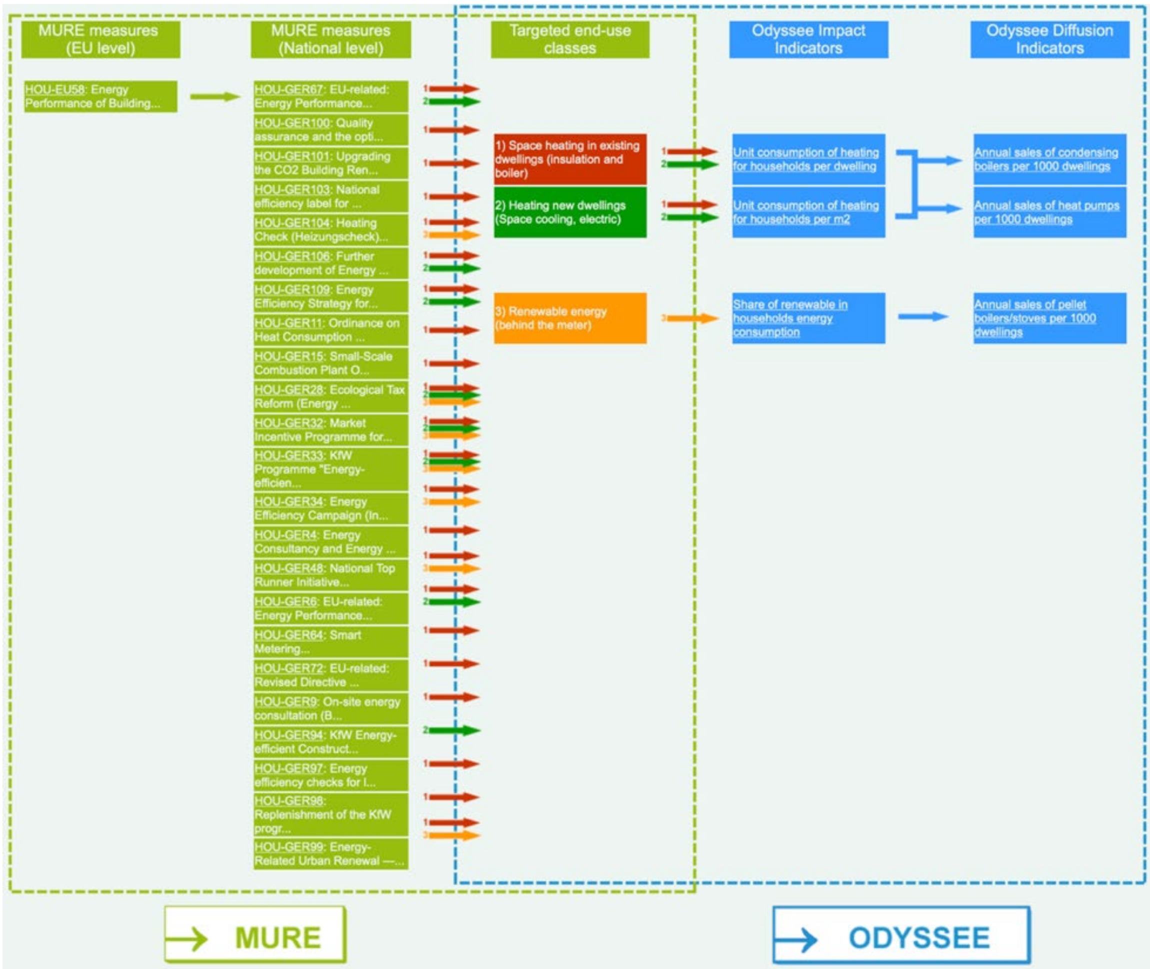

Figure 10. Policy mapper for households in the United Kingdom *(ODYSSEE-MURE, 2020)*.

EU Residential Energy Patterns

The residential sector consumed approximately 26% of the total primary energy in the EU, the second largest behind the transportation sector (ODYSSEE-MURE, 2020). Nonetheless, the residential sector experienced the largest energy consumption reductions in 2016 compared to the year before at 3.1% (Tzeiranaki, 2019). Comprehensive and robust legislative measures and policy initiatives introduced and implemented at the regional, national, and local levels in the European Union (EU) are key factors in driving overall residential energy consumption significantly down (Marina, 2018). As a result, EU final residential energy consumption patterns show a clear trend towards energy savings and reductions over the past decade (Figure 11). This is directly attributed to the adoption of mandatory energy conservation measures (ECMs) and green building policies. The average EUI for an apartment building in the EU stands at 158 KWh/m^2/YR (50 Kbtu/SF/Year) (Eurostat, 2020).

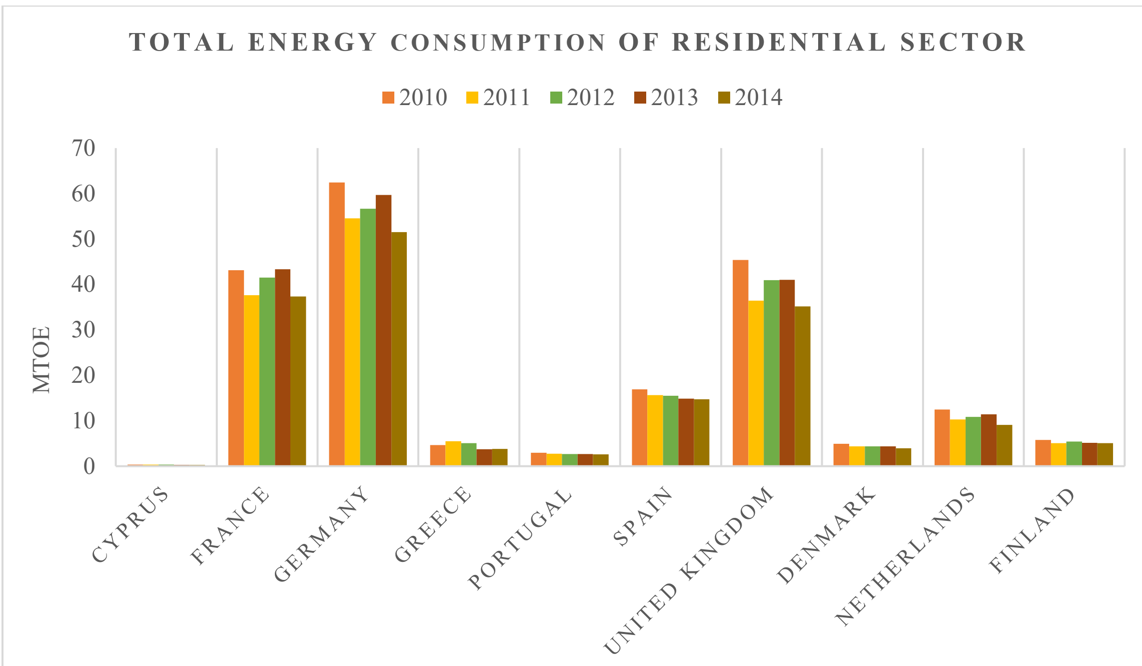

Figure 11. Total residential energy consumption trends in the EU *(European Commission, 2020)*.

The EU experienced a 2.1% per year reduction in final residential energy consumption between 2000 and 2016 (Figure 12). To that end, EU residential primary energy consumption decreased from 290 Mtoe in 2000 to 284 Mtoe in 2016 (Tzeiranaki, 2019). Cumulatively, residential energy consumption is at its lowest rates of the last two decades. Similarly, final residential energy consumption per capita decreased by 11% from 2005 to 2016 (Figure 13) (Tzeiranaki, 2019). Furthermore, residential energy use per dwelling has also experienced significant reductions in the EU (average rate of 1.5% per year), directly accredited to the adoption of mandatory ECMs and green building policies paired with financial investments and public awareness campaigns (Figure 14 & 15). Following similar trends, residential energy consumption per m^2 also experienced significant reductions in the past decade (Figure 16).

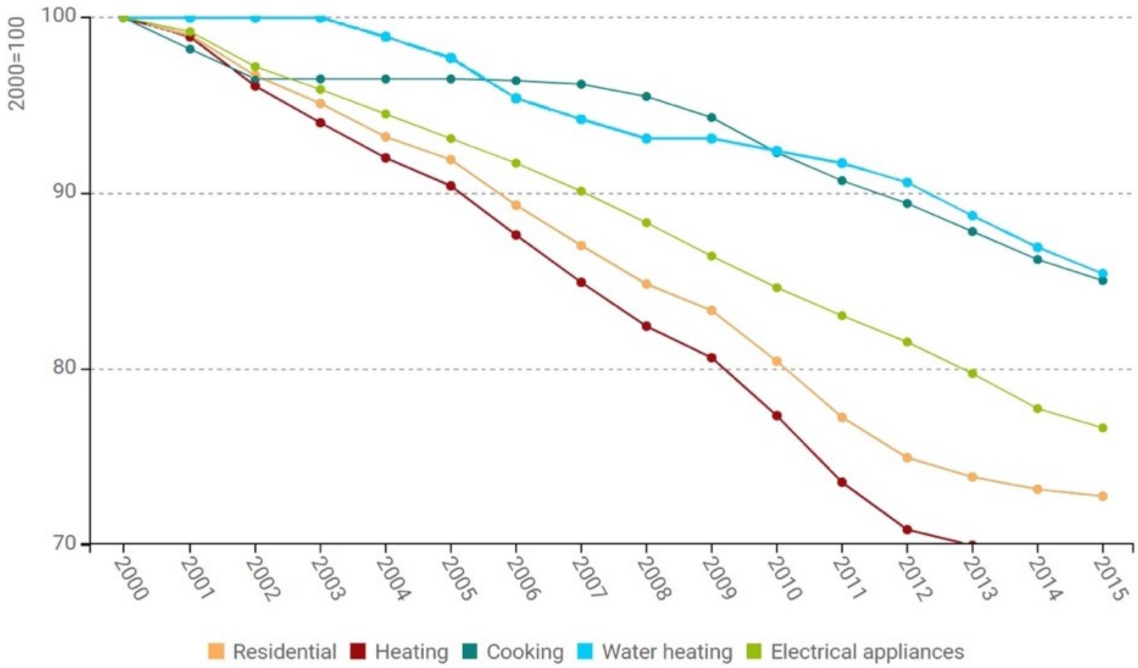

Figure 12. Percentage energy efficiency progress trends in the EU *(ODYSSEE-MURE, 2020)*.

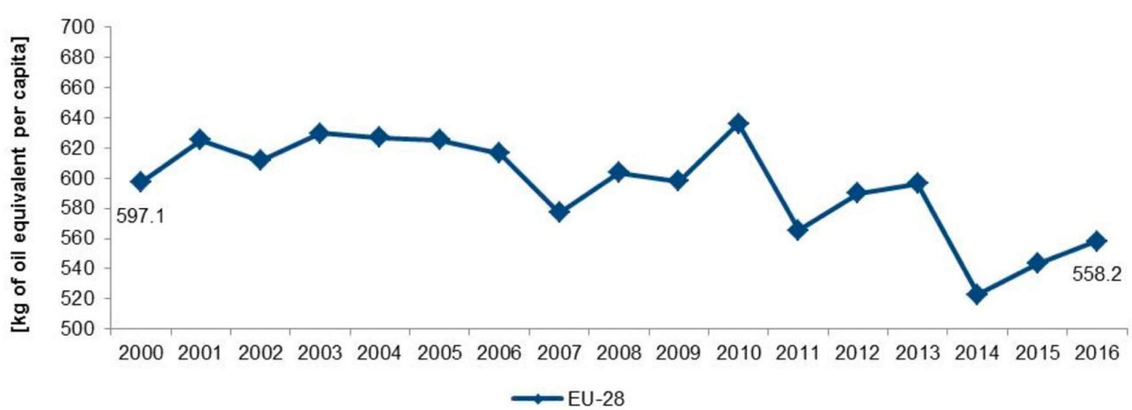

Figure 13. Final residential energy consumption per capita in the EU *(Eurostat, 2020)*.

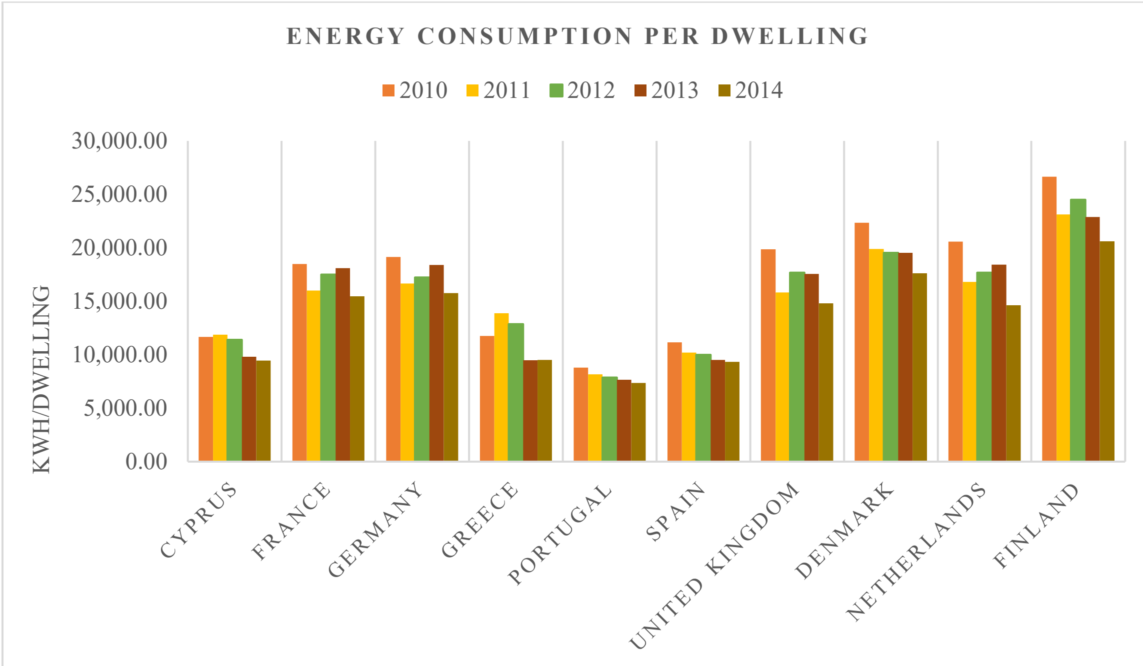

Figure 14. Total residential energy consumption per dwelling in the EU *(European Commission, 2020)*.

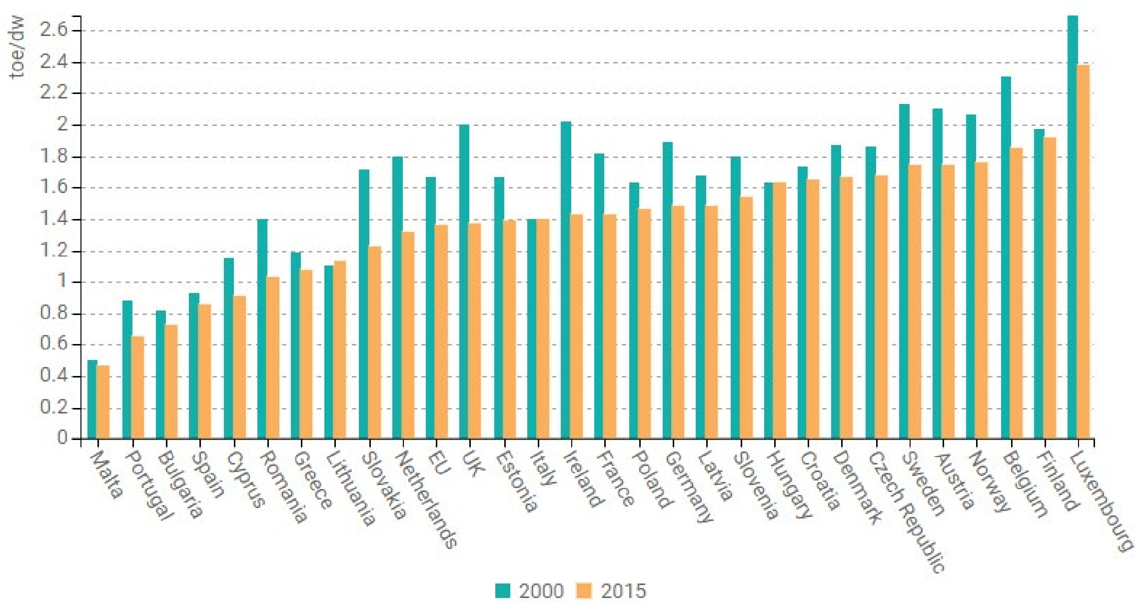

Figure 15. Average residential energy consumption per dwelling in the EU *(ODYSSEE-MURE, 2020)*.

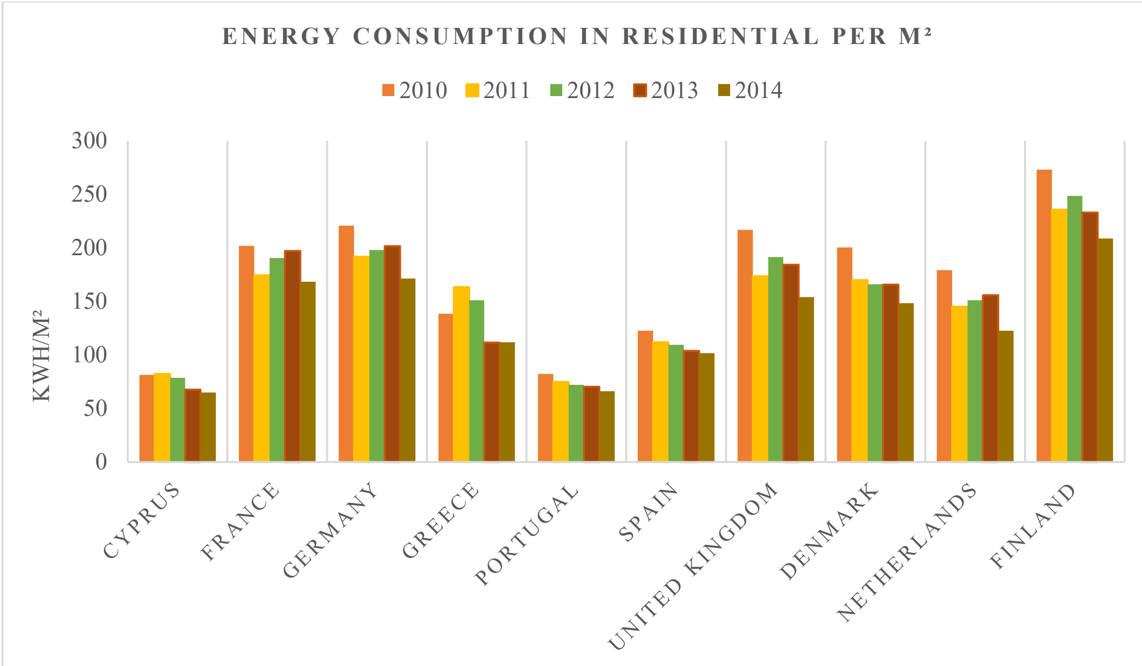

Figure 16. Total residential energy consumption per m^2 in the EU (European Commission, 2020).

Residential electricity consumption has also seen consistent reductions at the EU level (-0.4% per year) (Figure 17 & 18). Cumulatively, the residential sector in 2015 amounted for 44% of the total final energy use savings (230 Mtoe) in the EU, the largest percentage amongst all contributing sectors (Figure 19). EU household energy efficiency improved by approximately 28% since 2000. The next section highlights the impact of the various policies on energy consumption patterns in 3 EU nations: Germany, France, and the UK.

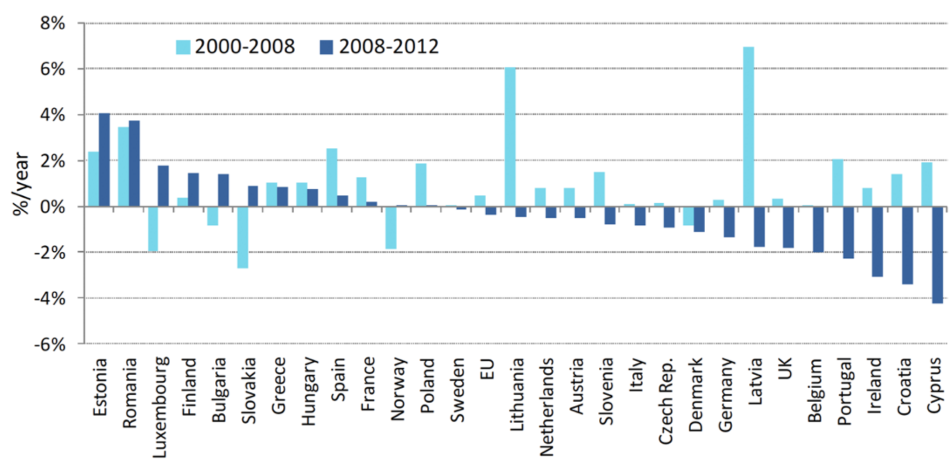

Figure 17. Electricity consumption per dwelling trends in the EU *(ODYSSEE-MURE, 2020)*.

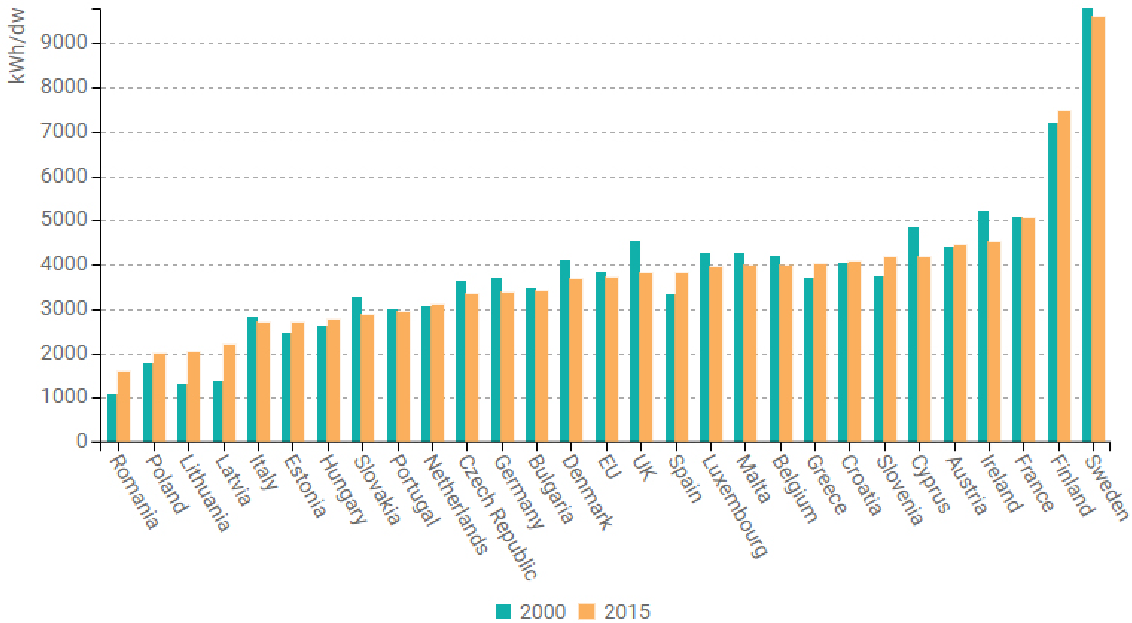

Figure 18. Electricity consumption per dwelling trends in the EU *(ODYSSEE-MURE, 2020)*.

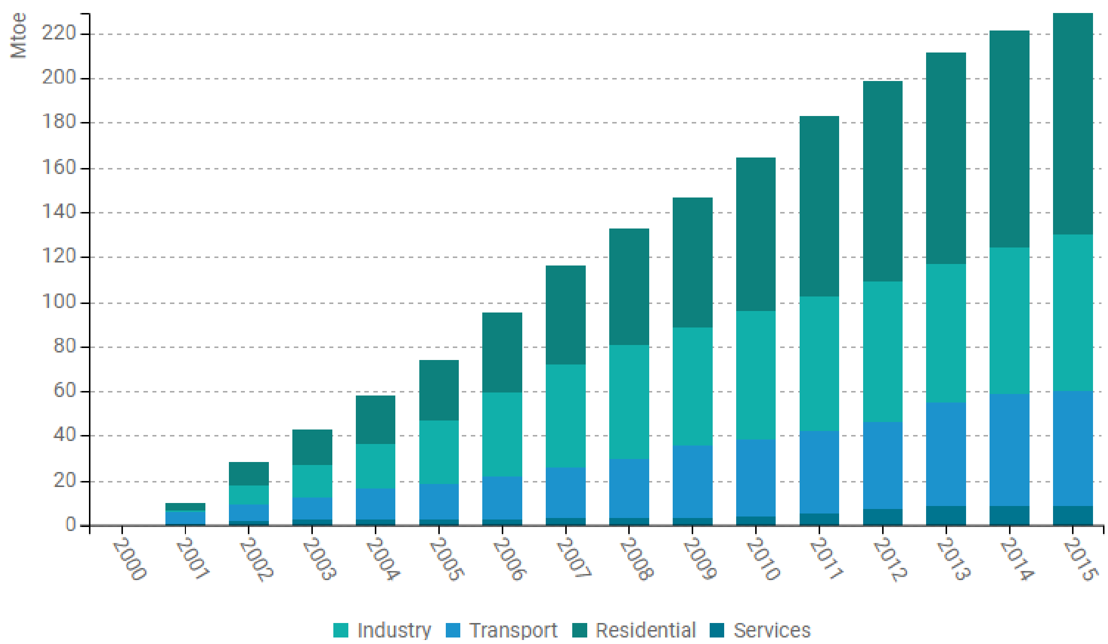

Figure 19. Total final energy savings trends in the EU (ODYSSEE-MURE, 2020).

Germany

German households account for about 25% of total primary energy demand in the country. Space heating constituted the majority of that demand at 68%. Germany utilized several energy conservation regulations to reduce its energy consumption and associated greenhouse gas emissions. The first such performance-based code was initiated in 2002. The EnEV required energy calculations to set anticipated measurable benchmarks for residential energy consumption. The regulation focussed on both energy using systems and thermal envelope components. Furthermore, the country set a nationwide goal of carbon-free buildings by 2020. Germany's residential energy policy approach adopted a hybrid paradigm, encompassing a bottom-up and top-down framework system. The framework model utilized market-driven policies, focusing on demand-side and augmented with a robust level of public engagement. The end result of these measures and policies set forth by the German government was an 8% reduction of residential energy consumption between 1990 and 2014. Furthermore, German households consumed less energy than their English and French counterparts. Over the period between 200 and 2016, total energy consumption per dwelling experienced a cumulative 30% reduction (ODYSSEE-MURE, 2020).

France

The French building sector consumed about 45% of total energy generated in the nation, the largest by far in comparison with other sectors. Similarly, the residential sector also consumed the largest amount of electricity, constituting approximately 36%. 21% of CO2 emissions were attributed to the residential sector in 2015. The French government introduced rigorous building regulations, such as RT2012, to set specific building performance requirements to reduce energy consumption patterns and curb greenhouse gas emissions. The measure requires residential buildings use no more than 40-65KWh/m2/pa. France started introducing performance-based codes in 2005 (ADEME, 2015). RT2012 covered several building components including thermal envelope, domestic hot water systems, HVAC, lighting, and heat recovery. In aggregate, the code aimed to yield buildings that are 40% more efficient than their 2005 counterparts. Furthermore, it calls for energy positive buildings by 2020. Cumulatively, France experienced a 26% reduction in residential energy consumption between 1990 and 2010 (Figure 6) (ODYSSEE-MURE, 2020).

United Kingdom

The residential building sector in the United Kingdom consumed approximately 30% of the total primary energy. The United Kingdom introduced and adopted comprehensive policies such as updated building regulations, EU product standards, smart metering, and supplier obligations. The main objective of all these policies and measures is to reduce energy consumption patterns and curb greenhouse gas emissions. Building regulations were introduced as early as the 1970s as a primary method to promote energy efficiency enhancements and energy savings in residences. Supplier energy efficiency obligations were instituted in the early 1990s as a mean to incentivize energy suppliers to install and promote residential energy efficiency measures. The 2010 L1A and L2A performance-based codes required set benchmarks towards achieving certain levels of target emission rates. The codes addressed thermal envelope, HVAC, lighting, and hot water systems performance. As a result of all the policies and measures adopted in the UK over the past decade, residential energy consumption was reduced by 22% since 2000. Moreover, the residential sector experienced significant energy usage reductions over the period between 2000 and 2017 amounting to a 32% reduction in water heating, 30% in cooking, and 8% in electrical appliances. Final residential energy consumption was 37 Mtoe in 2017, a reduction of approximately 20% from 2000. The majority of energy savings can be attributed to the robust energy-efficiency policies and measures adopted within the last decade. Specifically, the downward trend in energy consumption is directly related to the implementation of robust progressive building regulations encompassing heating systems upgrades, improved insulation and thermal transmittance requirements, high performance glazing systems, smart metering, and more efficient appliances (ODYSSEE-MURE, 2020).

1.1.1 Conclusions

Global residential energy consumption patterns have been experiencing a consistent growth in the past decade. The European Union is not immune to these forecasts and trends. Moreover, Europe is very susceptible to fluctuations in the energy market. This holds true to the Europe's residential sector, where residential buildings accounted for 25-40% of total energy consumption in 2016 and 20-35% of greenhouse gas emissions. The ever-increasing trends of larger homes and the proliferation of electronic equipment and appliances have amplified energy and electricity demand within the EU's residential sector. However, the EU's adoption of mandatory legislative measures and policy initiatives have successfully offset these trends. The systematic and comprehensive nature of these measures were instrumental in achieving the benchmarks set forth. To that end, the three-prong approach of regional, national, and local policies was a key factor in the overall success of the various measures. The introduction of energy policies and green building measures such as The Energy Efficiency Directive (EED), Energy Performance in Buildings Directive (EPBD), Energy Labeling Directive (ELD), Eco-design Directive (EDD), Minimum Levels of Energy Taxation Directive, and Renewable Energy Directive (RED) were key drivers in shaping a new paradigm for the residential sector. To that end, the EU's all-inclusive bottom-up approach utilized the following measures and instruments to improve energy efficiency and reduce overall consumption: high-performance design, energy labeling, energy efficiency directives, energy performance benchmarks and metrics, targeted subsidies, educational campaigns, energy supplier obligations, and various monetary tools and incentives. Collectively, the introduction and implementation of mandatory robust energy conservation measures and building policies have led to significant reductions in energy consumption in the EU, accounting for a 30% reduction in final residential energy consumption between 2000 and 2016. In total, residential energy savings reached approximately 100 Mtoe since 2000. Residential energy savings have yielded significant reductions in overall greenhouse gas emissions in the EU. To that end, the EU has already set ZEB targets for all new building within its EPBD framework. It's imperative to adopt a mandatory all-inclusive comprehensive approach targeting various scales and scopes to effectively change behavioural and consumption patterns. The EU's adoption of such approaches, focusing on robust energy policy measures and green building initiatives, has yielded significant savings over the past decade. Lebanon needs to undergo a paradigm shift, similar to that of the EU, to effectively impact its overall energy consumption patterns and overall building practices. The following measures and initiatives should be adopted: enforceable legislative frameworks for residential green construction and energy conservation, enforceable comprehensive national energy action plan, performance-based building codes, monetary and fiscal incentives towards green construction, and public awareness and educational campaigns.

Background on Residential Energy Patterns in Lebanon

Lebanon is a highly urbanized, middle-income country. However, decades of war, political instability, and corruption have left Lebanon with severe socio-political, economical, and environmental scars. In the aftermath of the 15-year civil war, significant areas of the country including the capital Beirut laid in ruins and disarray, during which, the environmental sector didn't fare much better. Furthermore, lack of comprehensive robust environmental policies has stamped a severe mark on the environment. Lebanon boasts a dismal environmental track record. Air pollution has been recognized as one of the most pressing public health issues facing the country, especially in densely populated urban areas as Beirut (Figure20). World Health Organization findings indicate that pollution levels in Beirut exceed all international standards. Lebanon is ranked 5th in the level of outdoor air pollution among 91 countries surveyed by the World Health Organization (WHO, 2019). Furthermore, Beirut has been ranked as one of the most polluted cities in the world. To that end, figures released by the World Health Organization indicate that Beirut has the 176th highest level of outdoor air pollution among 1,082 cities in the world. Beirut also ranks as the 63rd most polluted city among 159 cities in the upper-middle income countries (WHO, 2005). The World Health Organization based its findings on air quality metrics of cities and countries based on the annual mean concentration of particulate matter (PM10). With estimated average levels of 200µg/m^3 for particulates, the potential economic, environmental, and social impacts of air pollution in Lebanon are quite grave and alarming (Azar, 2010).

The energy and electricity sectors were one of the hardest hit sectors in the country as a result of decades of conflict and war. The electricity sector's infrastructure experienced severe destruction and neglect throughout the 15-year Lebanese civil war (Dagher, 2010). Moreover, the country's energy infrastructure including power plants and distribution networks were decimated and severely outdated. The complete and utter dismantling of Lebanon's public electricity infrastructure resulted in the rise of unregulated private generation, dubbed as the electricity mafia. As a result, the country experiences severe energy shortages and consistently fails to meet the demands of domestic energy needs. Lebanon imports more than 90% of the fuel it needs for its primary energy demand, primarily petroleum-based products. The heavy dependency on foreign fuel sources paired with unreliable and outdated energy production systems creates unsettled socio-economic and environmental conditions. As such, the energy and electricity sector, mainly thermal energy power plants, are major contributors to air pollution and greenhouse gas emissions in the country. Thermal plants are largely responsible for providing and meeting the primary electrical needs of the country. To that end, it's estimated the building industry consumes anywhere between 45% at the low end and 75% at the high end of total electricity demand, most of which is generated in antiquated power plants utilizing petroleum fuel oil as the main source. To that end, energy generation accounts for the significant percentage of air pollutant emissions in the country. About half of the electricity generated is distributed to and consumed by the residential market. The residential sector is a major contributor to air pollution, accounting for approximately 30-45% of total energy end-use consumption in Lebanon and its associated emissions (Yathreb, 2016). This section provides an overview of the energy and electricity sector in Lebanon and its impact on air pollution.

Figure 20. Image and map showing air pollution conditions in Lebanon (Google Images)

1.1.2 Climate

Located on the eastern coast of the Mediterranean, Lebanon has a warm temperate climate (Figure 21). The climate is characterized by dry hot summers with little precipitation (June–September), and wet cool winters (December–March). Nearly 70 percent of precipitation occurs between November and March. The coastal areas experience higher temperatures and humidity levels during the summer month, reaching up to 30°C, while the mountain regions experience colder temperatures and heavy winter snow. The Climate of Lebanon can be classified as Csa climate, a mild Mediterranean climate with the warmest month above 22°C and the coldest between 18°C and -3°C (Figure 22). The climate further inland can be classified as BSh climate, a hot and dry climate with the annual average temperature above 18°C. Lebanon has four distinct climate zones (Figure 23). Zone 1 is the coastal zone. The western mid-mountains are categorized under zone 2. Zone 3 is the inland plateau and zone 4 encompasses the high mountains (Table 2). 70% of the Lebanese population live in coastal zone 1. Climate change, manifested through rising sea levels and increasing temperatures, is a major issue in the country due to its wide-ranging implications. Climate change is projected to affect the densely populated coastal urban areas that house the country's main infrastructure and over 85% of the Lebanese population. These populations are highly susceptible to sea level rise, which is projected to cost $140 million in damage by 2040 (US AID, 2016).

Figure 21. Image showing the Mediterranean region and Lebanon

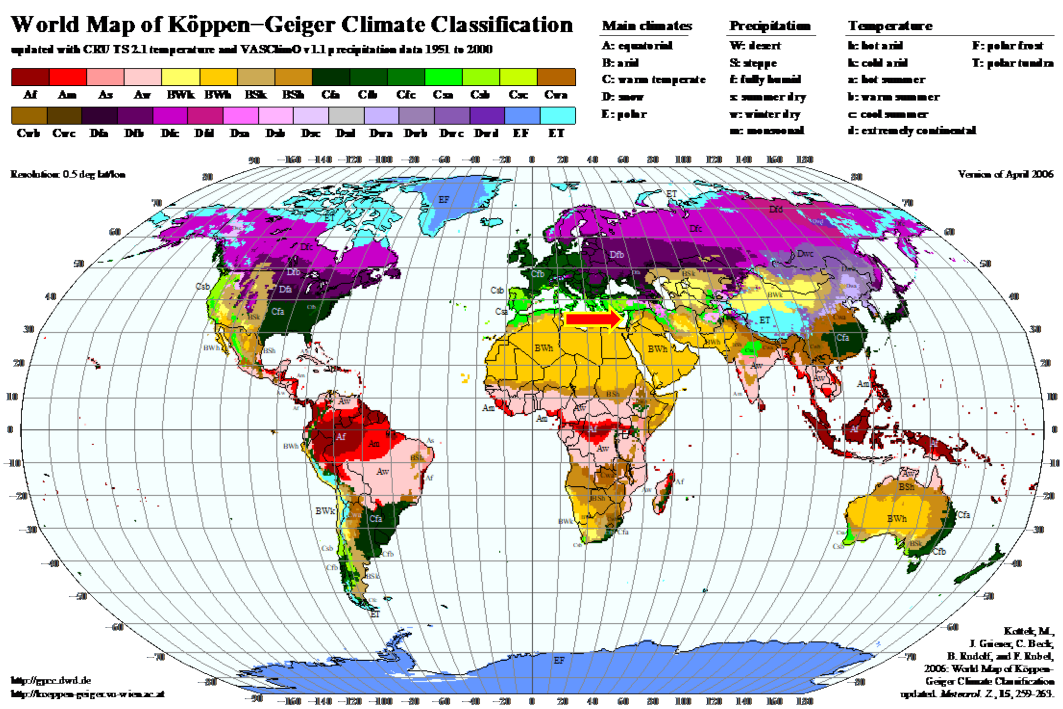

Figure 22. World map climate classification

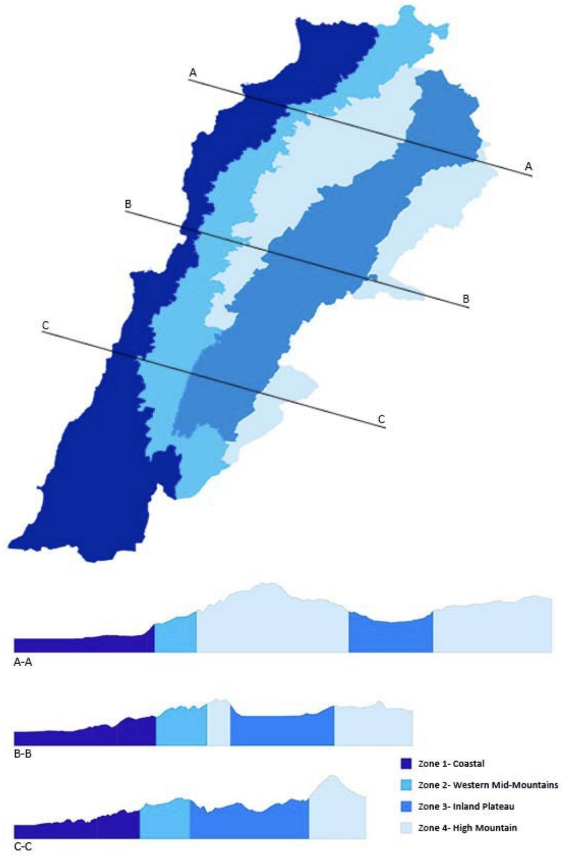

Figure 23. Map of Lebanon with the different climatic zones based on altitude

Table 2. Lebanon's 4 climate zones (Thermal Standard, 2010)

Climatic Zone	Climatic Sub-zone	Winter	Summer	Daily Gap
1 Coastal	**1A** Altitude < 400 m	Warm and short	Hot and humid	Small all year
	1B Altitude > 400 m	Cold and long increasing with altitude	Hot and humid with maximum daily temperatures differing slightly from 1A	
2 Western Mid Mountain	No Sub-zone	Cold and long increasing with altitude	Cool and Moderate summer	More pronounced than the daily gap of zone 1
3 Inland Plateau	No Sub-zone	Colder and longer than the winter at same altitudes in zones 1 & 2 (min temperatures lower than zones 1 & 2)	Hot and dry summer, but cool at night. The min temperatures are lower than zones 1 & 2 and the max temperatures are higher. Very low humidity.	In summer the daily gap is high and varies according to the year.
4 High Mountain	No Sub-zone	Long and rigorous	Cool	Moderate to high in Eastern Mountain

1.1.3 Energy Patterns

Lebanon is an energy intensive country, exceeding many neighboring southern Mediterranean nations. Moreover, energy consumption patterns have been increasing over the past decade and are projected to continue to grow over the next 10 years (World Energy Council, 2016). This trend could be attributed to many factors, one of which is a population and an economic boom (Figure 24). The country experienced two major population booms; the first credited to the post war 1990 economic boom resulting in a large population migration back to Lebanon; the second attributed to the influx of Syrian refugees after the Syrian civil war. Petroleum consumption patterns followed a steady trend of growth and increase in demand, triggered by the economic and population explosion (Figure 25). Moreover, petroleum consumption patterns have been predictably impacted by significant historical markers such as the post-war reconstruction, ongoing political turmoil, and the Syrian civil war. Correspondingly, energy consumption patterns have followed a similar trend to petroleum consumption patterns. Nonetheless, fuel consumption and energy demand are forecasted to grow over the next 10 years. To that end, Lebanon primarily uses imported liquid petroleum gas to meet more than 90% of its primary energy needs (Azar, 2010). The country is heavily dependent on oil imports, further destabilizing its already unreliable energy market. Lebanon has one power utility, seven thermal power plants (3 operate on heavy fuel oil and 4 on gas). 96% of the electricity is generated through thermal plants, which generated 12,237 GWh in 2015, far below the demand of 20,368 GWh (Lebanon Ministry of Environment, 2020). As a result, Lebanon experiences chronic power outages. This gave rise to an unorganized and unregulated private generation sector that provides anywhere between 30 and 40% of the needed power, depending on geographic location within the country.

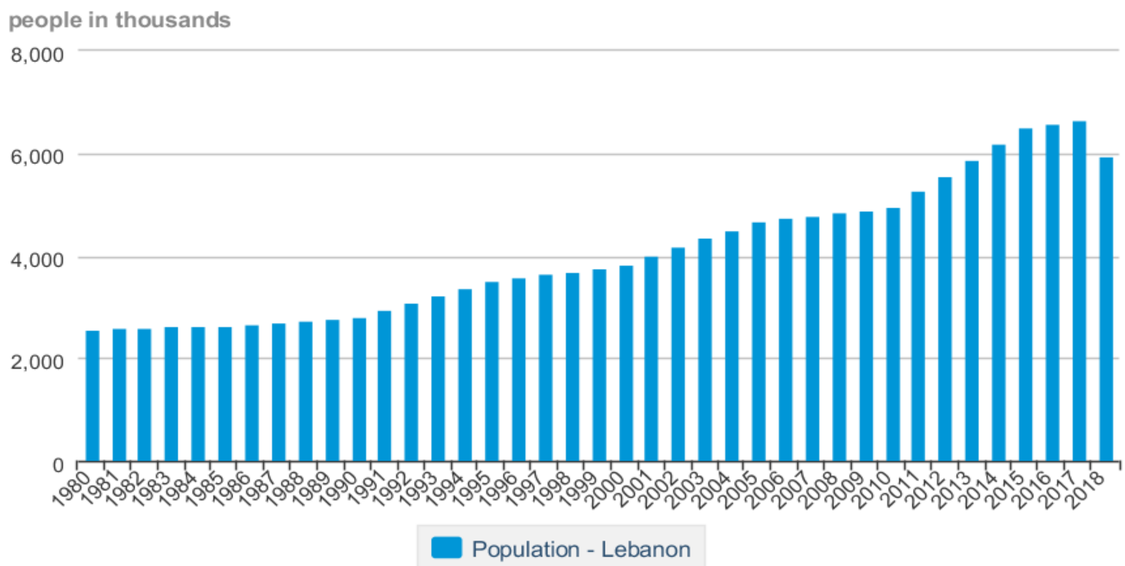

Figure 24. Population growth trends in Lebanon (U.S. EIA)

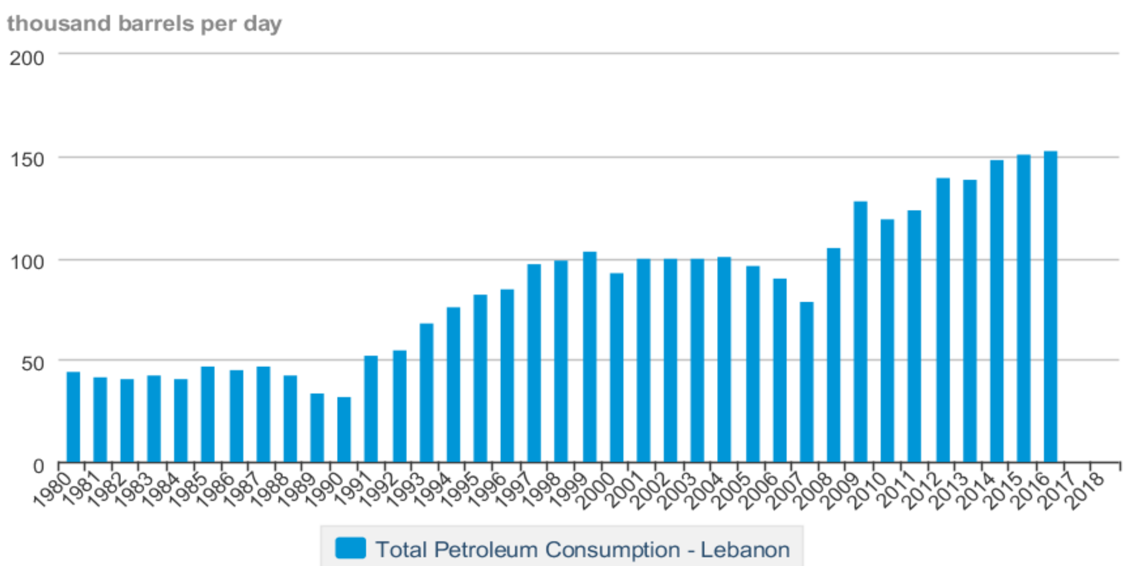

Figure 25. Petroleum consumption patterns in Lebanon (U.S. EIA)

Due to unreliable energy markets and a deficient infrastructure, the energy and electricity sector have failed to meet the demands of domestic energy needs. The energy production market in Lebanon is volatile and unpredictable (Figure 26), causing severe shortages in supply and inability to meet primary consumption needs. As a result, consumptions patterns don't match production patterns (Figure 27), resulting in a heavy dependence on foreign oil imports and unstable energy markets. In 2010, the country imported 120,000 barrels per day (bbl/d) of refined oil products, accounting for over 90% (97% in 2014) of total primary energy demand in the country (Yathreb, 2016). Similarly, energy consumption per capita follows a similar trend to petroleum and energy consumption patterns (Figure 28). Energy consumption patterns are heavily influenced and driven by market forces and major geo-political events.

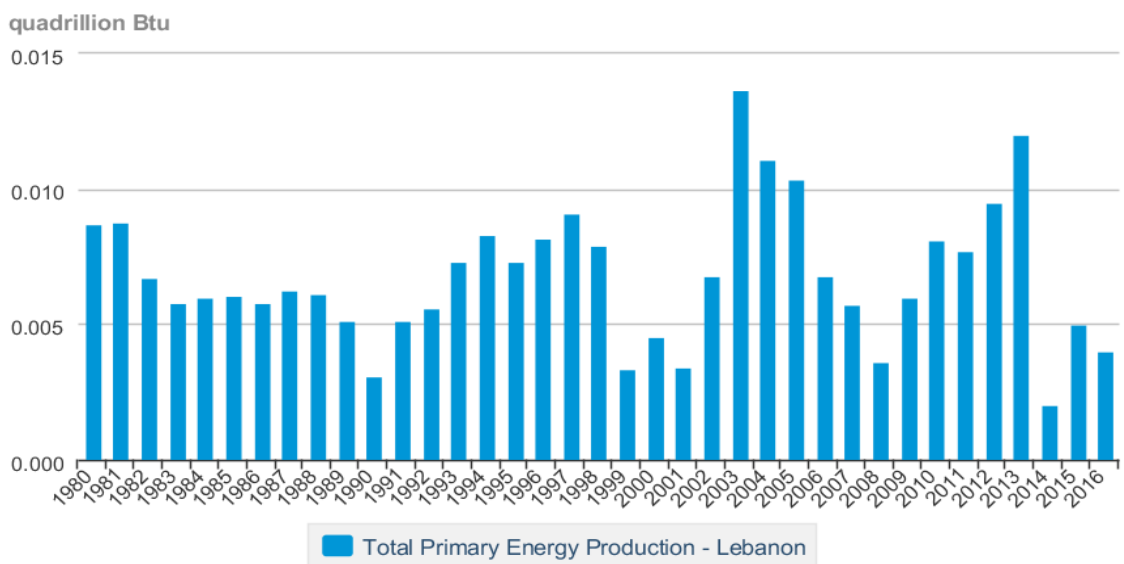

Figure 26. Energy production patterns in Lebanon (U.S. EIA)

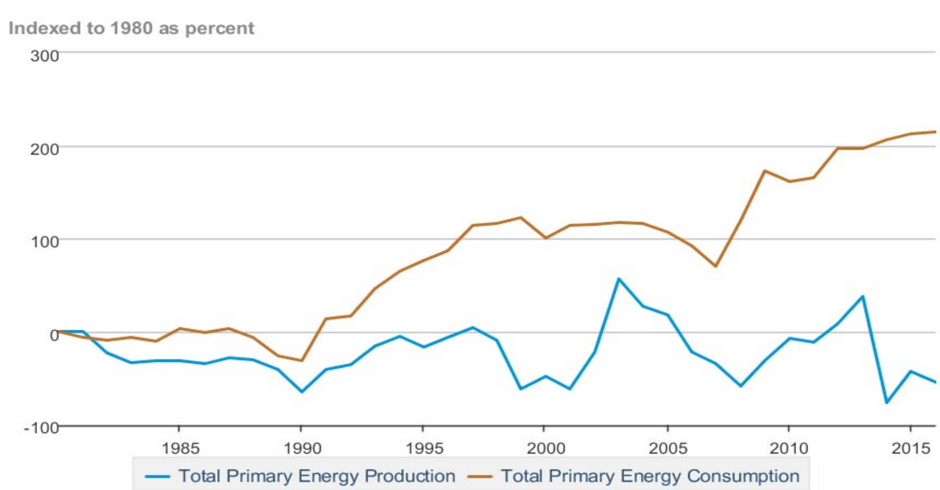

Figure 27. Primary energy production and consumption patterns in Lebanon (U.S. EIA)

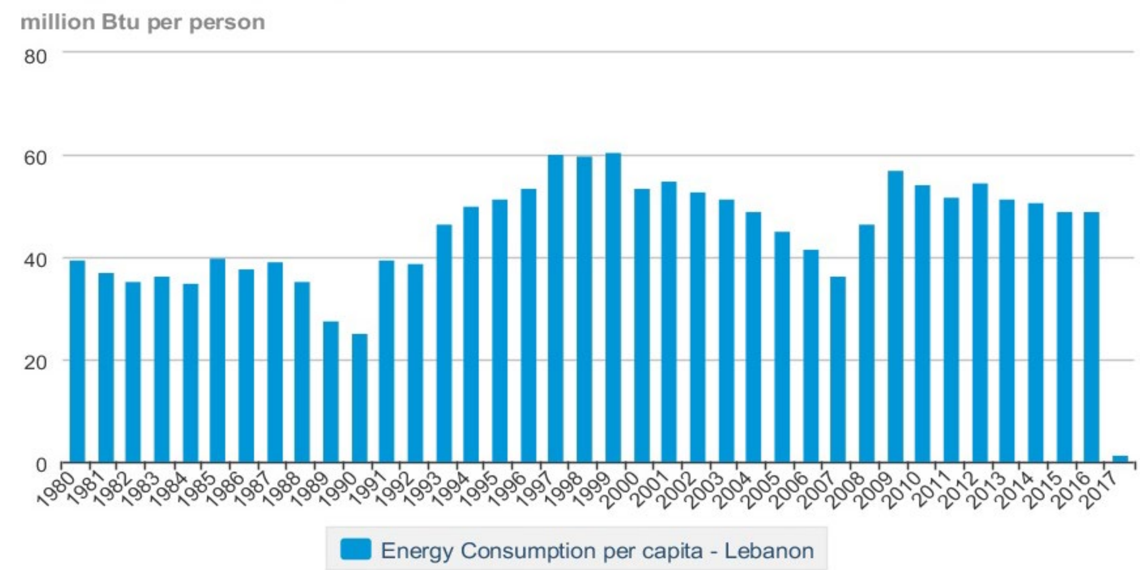

Figure 28. Energy consumption per capita patterns in Lebanon (U.S. EIA)

1.1.4 The State of Electricity

Lebanon's electricity sector has been plagued by corruption, inefficiencies, and monopolies. The crisis has pushed the country towards financial ruins. Frequent, albeit predictable, power cuts have hobbled the economy and daily lives of Lebanese citizens. Moreover, the heavily subsidized electrical sector has yielded one of the world's largest public debt burdens, amounting to $1 billion to $1.5 billion annually, mainly spent on fuel oil purchases (Missaoui, 2012) (Figure 29). According to International Monetary Fund (IMF), the accrued cost of subsidies totals approximately 40% of the country's total debt (2016). Furthermore, 90% of the electricity market is primarily controlled by state-owned Electricity of Lebanon (EDL), a public institution housed under the Ministry of Energy and Water (MEW) (Fardoun, 2012). EDL is tasked with the responsibility of generating, transmitting, and distributing electrical energy in the whole of Lebanon for roughly $2 billion each year, Lebanon (EDL) produces a mere 1,500 megawatts when local needs are at least twice as much to cater to the 5 to 6 million citizens. However, EDL is not able to satisfy consumption needs (13,200 GWh in 2006) as it frequently experiences severe shortages in generating capacity, yielding only a 50% coverage (10% in 2021). Electrical consumption patterns continue to exceed current generation capacity, resulting in sever power outages, blackouts, and a heavy reliance on private generation, primarily utilizing diesel fuel (Figure 30). EDL still cannot afford to purchase enough fuel to keep the lights on 24 hours a day. Gas-powered generators and their operators fill the void created by a strained electric grid (generator mafia). Private and self-generation markets are estimated to represent around 30-40% of all electrical generation (World Bank, 2009). Most residents receive between 10 and 13 hours of public power each day. To that end, residents turn to neighbourhood power-generator services to cover the remaining hours of the day. Thus, Lebanese consumers pay two electrical bills, one for EDL and the other for private operators, usually twice the public electrical bill. Lebanese pay the highest electric bills in the region, while experiencing the lowest quality service. Furthermore, the existing overtaxed power grid does not consider the additional burden of nearly 2 million Syrian refugees, whose consumption needs cannot be ignored either.

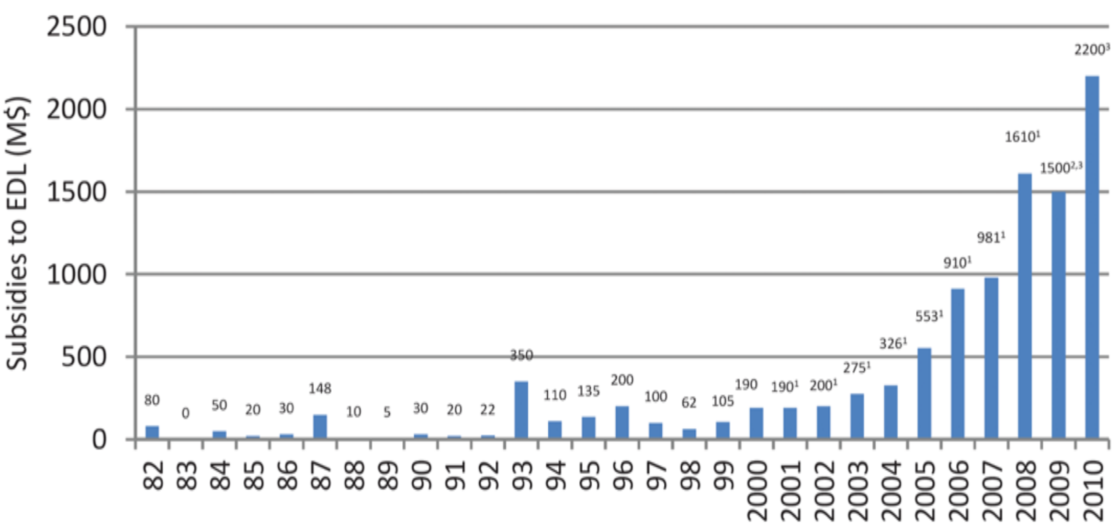

Figure 29. Electricity subsidies between 1982 and 2010 (World Bank, 2009)

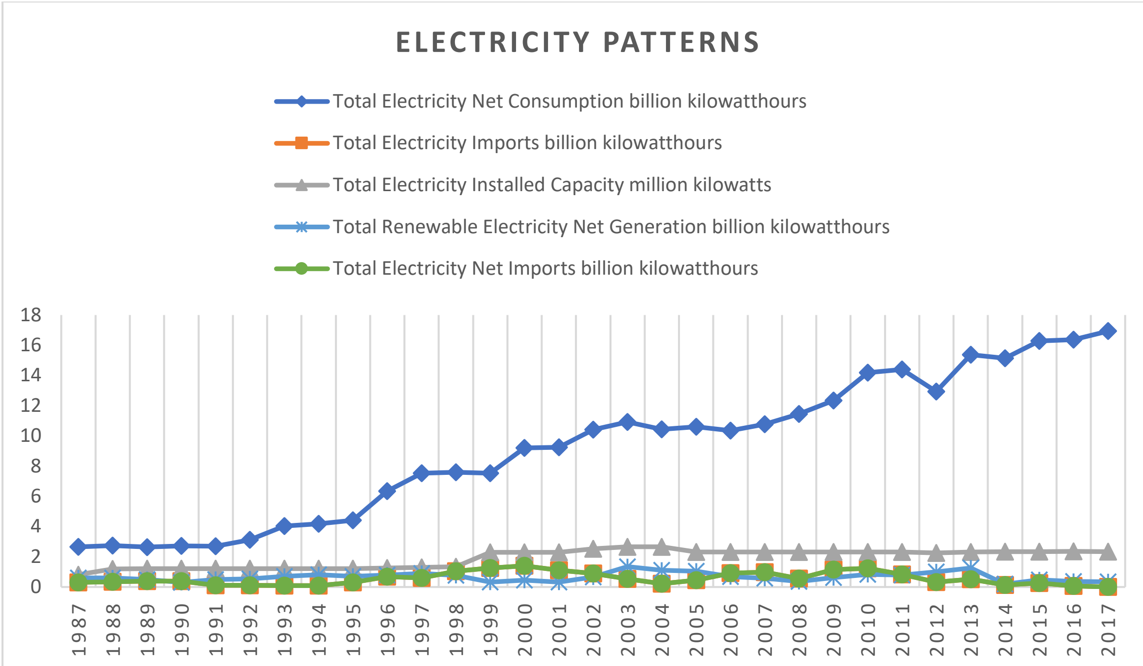

Figure 30. Chart highlighting electricity generation and consumption in Lebanon (source – EIA)

Aging and outdated state-owned power plants have not been able to meet 24-hour electrical consumption demands since 1975. As such, installed electrical capacity doesn't meet consumption demands, leading to substantial shortages in electrical generation capacity (Figure 31). For approximately $2 billion a year, Lebanon generates approximately 1,500 megawatts (MW), while domestic electricity needs are at least twice as much (Fardoun, 2012). The country's power plants have a maximum capacity around 2,000 MW, compared to peak demands of 3,400 MW. Public sector electricity generation accounts for about 50% of total electrical supply, while 50 % is provided via private generation at a consumer rate of $0.40/KWh. Citizens get around 10 to 13 hours of public electricity a day, divided into 4-6 hours increments. Residents turn to neighborhood private electricity providers to augment the outstanding hours of the day. Households are heavily reliant on private generation, a primarily unregulated and unchecked industry. As such, the private generation energy market is a major player in the country's overall energy market. In 2021, private generation accounted for up to 90% of electricity supply. Furthermore, the artificial cost of power billing has exacerbated the subsidies problem. Consumer public electrical cost ($0.015/KWh - 35lira/KWh) has not changed since the mid 90's, even though oil prices have increased drastically. For reference, residences pay 2.33 cents for the first 100 kWh consumed per month, then the rate increases to 3.67 cents for the fraction from 101 to 300 kWh, 5.33 cents for the fraction from 301 to 400 kWh, 8 cents for the fraction from 401 to 500 kWh and 13.33 cents for any consumption above 500 kWh. Moreover, electrical payment and billing collection is also inconsistent due to power losses through creaking transmission and siphoned power, costing EDL about half of the power its produces. As a result, EDL is approximately $4 billion in debt. Public utilities neither have the installed capacity nor the monetary capability to provide the public with 24-hr electricity. To further exacerbate the issue, the influx of 2 million Syrian refugees significantly overburdened the already overloaded grid, resulting in severe and more frequent blackouts (Fardoun, 2012). The main reasons behind those blackouts were the ageing power stations that did not receive proper maintenance, along with a growing demand exceeding the available supply.

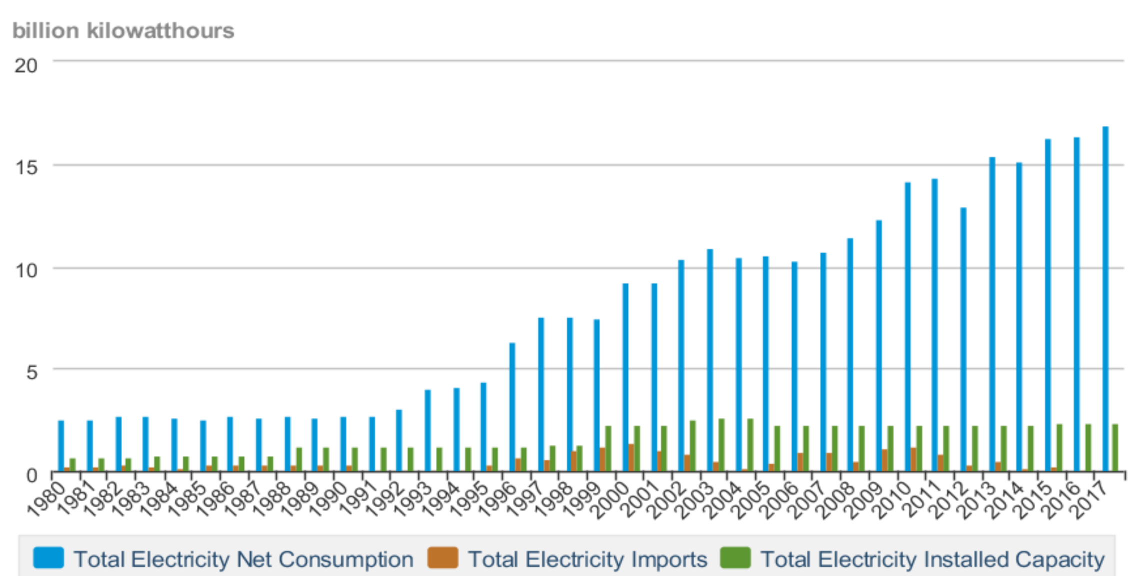

Figure 31. Electricity consumption and generation patterns in Lebanon (U.S. EIA)

1.1.5 The State of Air Pollution

Decades of un-regulated urban development and a heavily fossil-fuel dependent energy sector coupled with a severe lack of oversight have amplified air pollution problems in Lebanon, where air pollutant levels frequently exceed international air quality guidelines and standards (MOE/UNDP/ECODIT, 2011) (Figure 32). To that end, the distribution of the NOx and CO gas in the urban areas of Beirut exceeds acceptable international guidelines (Figure 33). Electricity generation and energy production constitute the main contributors of CO2 emissions (about 40% of total emissions), followed by the transportation, industrial, and residential sectors (World Bank, 2009) (Figure 34). Energy consumption trends have been increasing over the past decade and are expected to continue to propagate over the next decade. Correspondingly, carbon dioxide emission patterns follow a similar trend to energy consumption patterns (Figure 35). As a result, the World Health Organization (WHO) estimated a 100% of the population is exposed to pollution levels above the recommended guidelines (Figure 36). Moreover, governmental failure to regulate and protect the environment has severely impacted the country's natural resources and overall environment. As such, Lebanon was ranked 5th in the 2019 Pollution Index for Country, which examined air pollution in countries worldwide. The World Health Organization estimates the percentage of air pollution in Lebanon at 76%. The country's annual mean concentration of PM2.5 is 31 μg/m3, exceeding the recommended upper limit of 10 μg/m3. Furthermore, air pollution poses the most significant threat to the health of Lebanese citizens. To that end, a two-year study of nitrogen dioxide (NO2) in Beirut, from December 2004 to June 2006, showed an average concentration of 66μg/m^3 exceeding the World Health Organization recommended annual levels of 40μg/m^3 (Afif, 2009). Other studies have also shown that average levels of ozone (O3), carbon monoxide (CO), sulfur dioxide (SO2), and particulate matter have all exceeded WHO recommended guidelines (WHO, 2005). The energy sector, predominantly fossil-fuel based, is a major contributor to the pollution in Lebanon. Outdated plants, lack of routine maintenance, and unregulated private generation are all primary drivers of pollution.

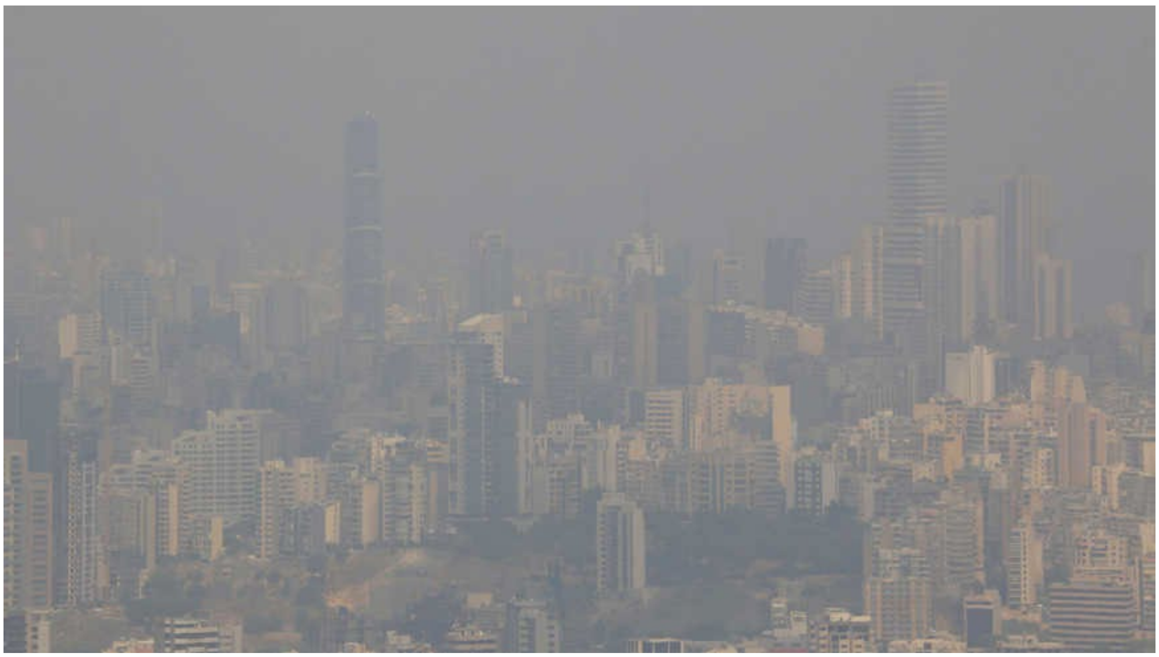

Figure 32. A view of Beirut shrouded in a haze of pollution, June 25, 2016 (REUTERS)

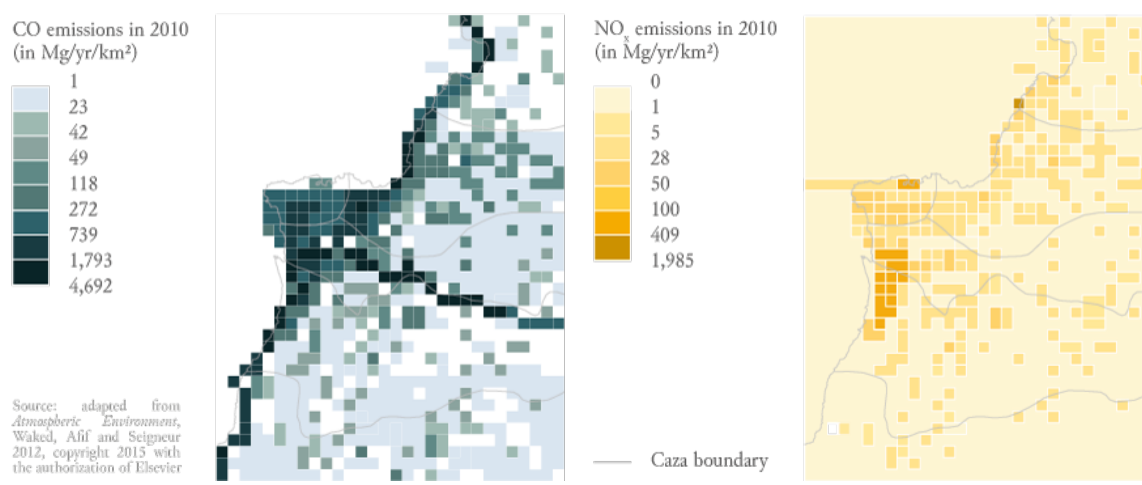

Figure 33. Air pollution in Beirut in 2010 (WHO, 2010)

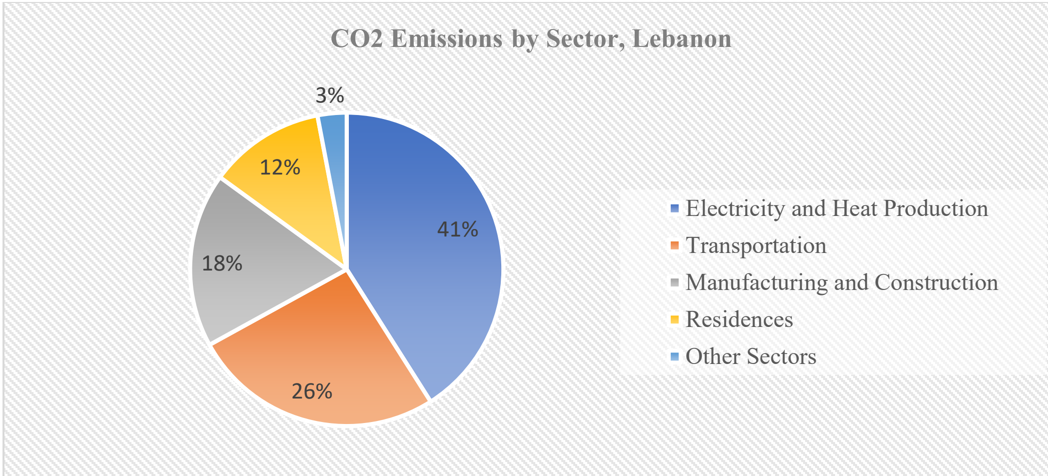

Figure 34. CO2 emissions percentage by sector in Lebanon (World Bank, 2009)

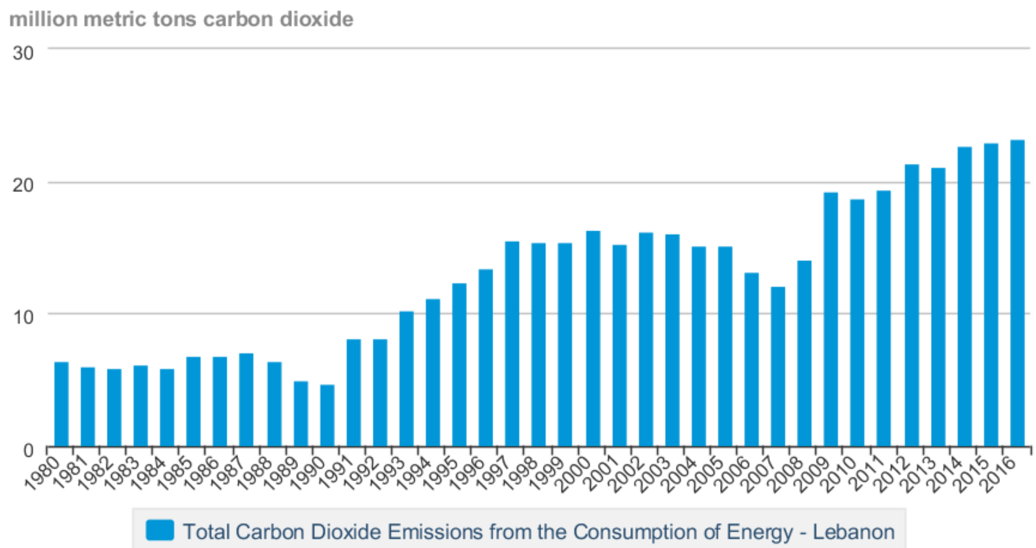

Figure 35. CO2 emissions from energy consumption in Lebanon (U.S. EIA)

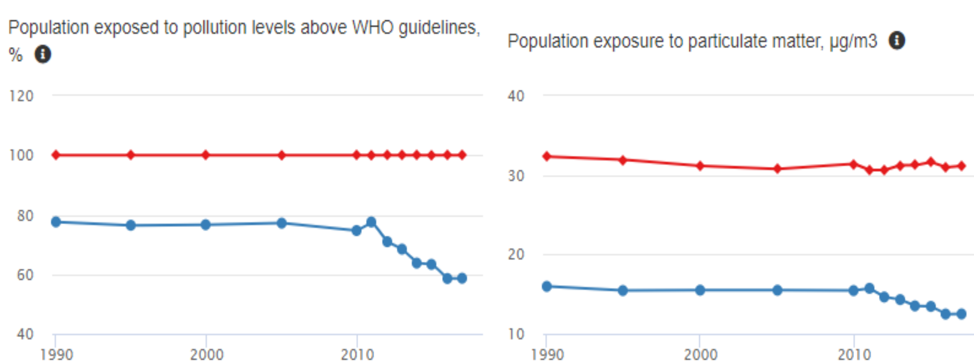

Figure 36. Percentage of Lebanese exposed to pollution levels above WHO guidelines (WHO, 2019)

Air quality in Lebanon is primarily affected by anthropogenic activities. The primary sources of air pollution could be attributed to the transportation sector, energy sector, industrial sector, and construction sector (Figure 35). However, the energy sector, mainly thermal power plants (stationary source), is the one of the leading contributors to air pollution in Lebanon. The industry is responsible for the unrelenting black plumes that plague the capital Beirut, emitting a myriad of pollutants such as hydrocarbons, carbon monoxide, carbon dioxide, sulphur dioxide, nitrogen oxides, soot, and particulate matter (MOE/UNDP/ECODIT, 2011). Furthermore, thermal power plants are by far the most prevalent producers of carbon dioxide emissions, comprising 39% of Lebanon's total carbon dioxide emissions in 2005. The impact of such plants on air quality is further amplified by the sulphur content of burning high-emission fuel such as heavy fuel oil. Most plants don't employ control equipment to mitigate emissions; their stacks aren't equipped with effective treatment units such as flue gas desulfurization, scrubbers, filters, and dust collection units (MOE/UNDP/ECODIT, 2011).

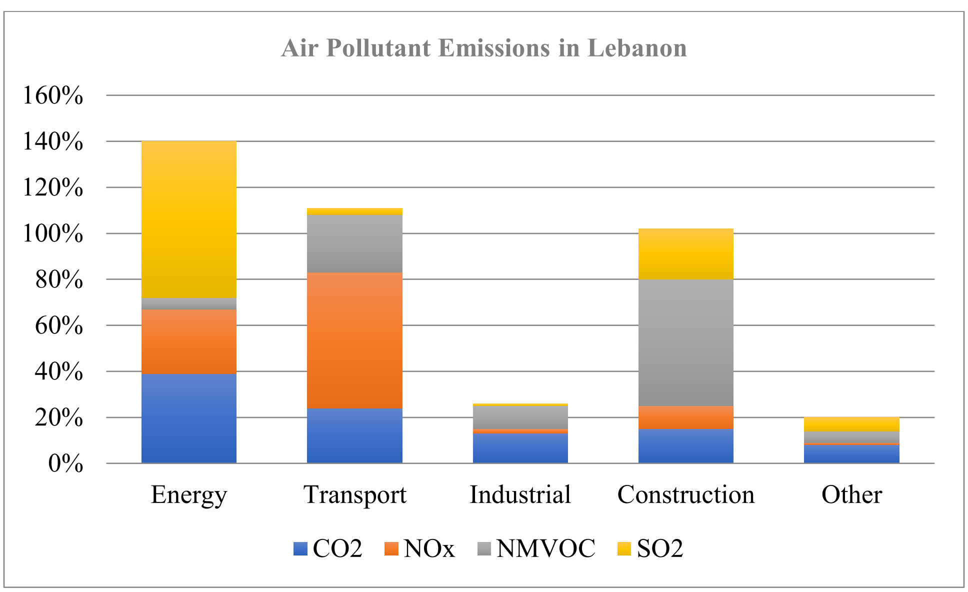

Figure 37. Contribution of sectors to national air pollutant emissions in Lebanon (World bank, 2009)

United States Agency for International Development 2012 data estimates a 229% increase in annual GHG emissions in Lebanon compared to 1990 levels, amounting to 24.34 MtCO2e (USAID, 2012). The energy sector constituted the predominant portion of the emissions at 21.14 MtCO2e. The key driver behind this increase in GHG emissions is the growing demand for energy due to population boom, economic development, system inefficiencies, and fuel types. State-owned aging thermal plants use petroleum fuel oil, along with exhaust from diesel generators, that exacerbates air pollution and smog. Alongside the antiquated and outdated generation systems, the plants also pose a severe health risk and cost. Air pollution can cause serious respiratory diseases. Studies have shown that chronic exposure to PM has been linked with higher instances of cardiovascular problems and respiratory disorders such as lung cancer and asthma. Furthermore, researchers have been able to establish a clear connection between air pollution and various illnesses such as rheumatic and coronary heart diseases, lung and stomach cancers, and pneumonia. (WHO, 2005). The World Health Organization estimated the annual cost of environmental degradation due to air pollution in Lebanon to be around 170 million dollars constituting 1.02% of GDP.

1.1.6 The State of Residential Sector and Energy Use

The residential sector in Lebanon consumes approximately 30-50% of the total generated electricity (compared to 25% in regional Mediterranean countries), constituting the largest amount of energy end-use consumption, and hence a significant driver of air pollution in the country (Figure 38). To that end, electrical residential demand increased from 3,080 GWh in 2009 to 5,750 GWh in 2014 (LCEC, 2018). The average Lebanese apartment building has an EUI between 135-220 KWh/m^2/yr. Residential electrical demand is largely composed of heating, cooling and dehumidification, equipment, lighting, and domestic hot water. The residential sector constitutes the largest user of thermal energy. The residential sector's substantial energy footprint is a major driver of air pollution patterns in Lebanon. Hence, it's a primary contributor to air pollution in the country. Lebanon has also seen a significant increase in energy consumption per dwelling between 2003 and 2009, due to the significant reduction of smuggled Syrian oil products after the civil war (Figure 39) (Missaoui, 2012). Moreover, the slow proliferation of green construction methodologies within the residential sector have had a major impact on energy consumption trends as well as air pollution. This could be directly attributed to weak legislative and institutional frameworks, subsidies of energy prices, and absence of a comprehensive national energy strategy (Missaoui, 2012). Furthermore, lack of public awareness and educational programs have also contributed negatively to sustainable development in general. To make things worse, most green energy and sustainable construction initiatives are voluntary in nature and lack meaningful enforcement mechanisms (Awwad E. K., 2012). To that end, Lebanese construction law is offering monetary incentives for voluntary thermal insulation of buildings (Yathreb, 2016). However, the construction law does not take into consideration the environmental impacts of construction and design practices in buildings. Consequently, energy efficiency measures and upgrades aren't widely adopted due to the lack of proper legislative system with adequate monitoring agencies for enforcing and monitoring green construction practices. Moreover, lack of public awareness and absence of robust energy conservation policies have had a detrimental impact on the proliferation of green residential construction in Lebanon. Nonetheless, interest in energy performance has increased in the last few years, albeit within the commercial building sector. However, since residential structures consume 30% of the total end-use energy in Lebanon (Yathreb, 2016), it's paramount to undertake a comprehensive and holistic analysis of residential energy conservation and efficiency. Nonetheless, sustainable residential construction remains primitive and deficient in Lebanon. Most residential buildings are not properly insulated, and in some instance, not insulated at all (Yathreb, 2016). This is directly attributable to the fact that none of the thermal insulation standards were never adopted and remain voluntary (EL Andaloussi, 2011). Similarly, the role of governmental and public agencies in promoting sustainable development is not adequately established yet. Residential construction and development are primarily driven by aesthetics in lieu of performance. As a result, the adoption and implementation of residential sustainable construction techniques and green building upgrades have been very slow and, in some instances, non-existent. The following are few of the barriers hindering the growth of the green residential market:

- Lack of a laws defining the Thermal Standards application.
- Lack of training and awareness programs for stakeholders.
- Lack of demonstration projects.
- Lack of institutional set-up and facilities for program implementation.

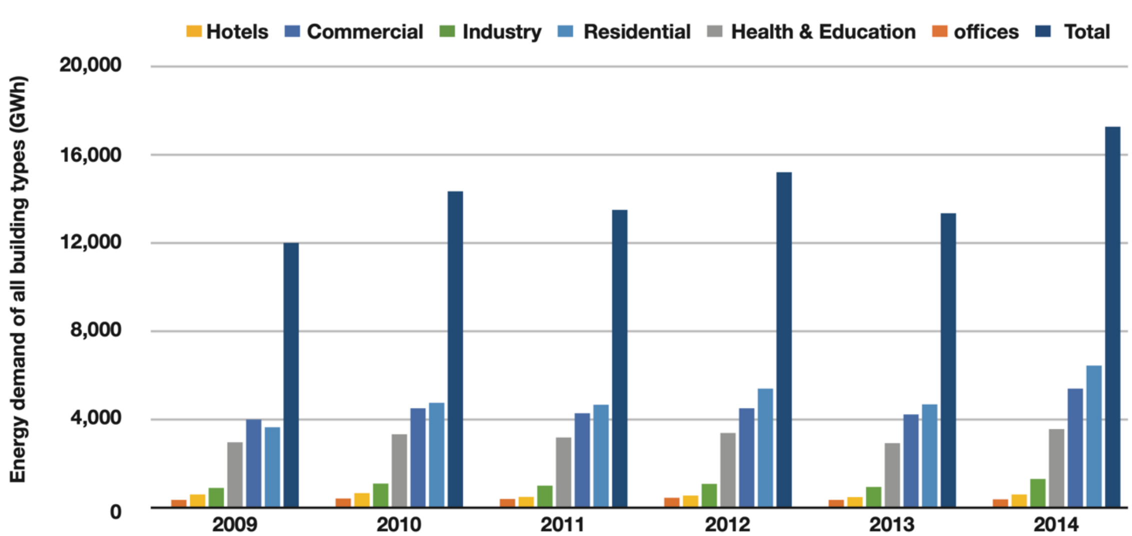

Figure 38. Energy demand (GWh) of the building sector (2009-2014) *(LCEC, 2018)*

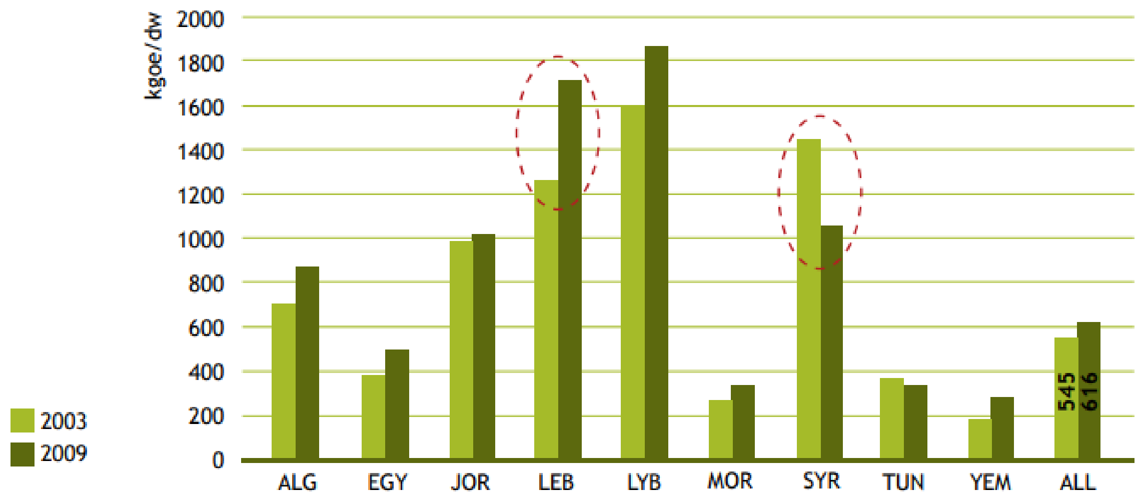

Figure 39. Energy consumption per dwelling in the Middle East region *(Missaoui, 2012)*

1.1.6.1 Apartment Building Sector

The Lebanese population is highly urbanized, with an estimated 90% living in cities. Most citizens live in standard residential blocks. The houses are typically apartments in multi-story buildings. Standard apartment buildings accounted for approximately 70% of the residential market in 2012 (BankMed , 2014). Moreover, 67 % of housing entails multi-floor apartment buildings (Yathreb, 2015). Independent houses made up the remaining 30% (Figure 40). 2018 statistics show apartments constituted 85% of Lebanese households (CAS, 2020). Similarly, 80% of total construction permits were issued for standard apartment blocks. Most apartment blocks are tailored for low to middle income households. Residences are generally family houses either rented for long term or owned. The average apartment area is approx. 170-200 m^2 (182 m^2 in 2017). However, the share of small residential units (100-150 m^2) accounted for 45% of total residential units in 2012, an increasing and prevalent trend in the past decade. Most apartment blocks are built for profit and to meet basic standards, with minimal or no attention to overall performance and comfort. Apartments blocks constituted around 67% of Lebanese households and 55% of these dwellings were built 25 years ago or older (BankMed , 2014) (Figure 40). Over the period between 2011 and 2016, the breakdown of construction permits by usage shows that residential buildings constituted the lion share of the construction market, accounting for 82% of total construction permits. Most residential construction permits were for standard apartment blocks (Figure 41). To that end, 70% of the population owned a home in 2012. However, the trend of homeownership is currently changing due to extremely high land and apartment prices.

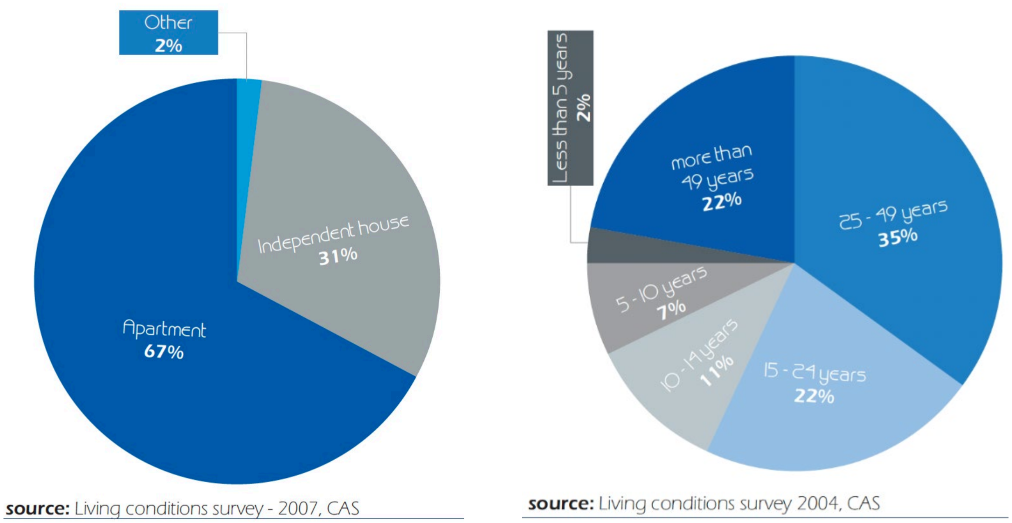

Figure 40. Housing characteristics in Lebanon (CAS, 2007)

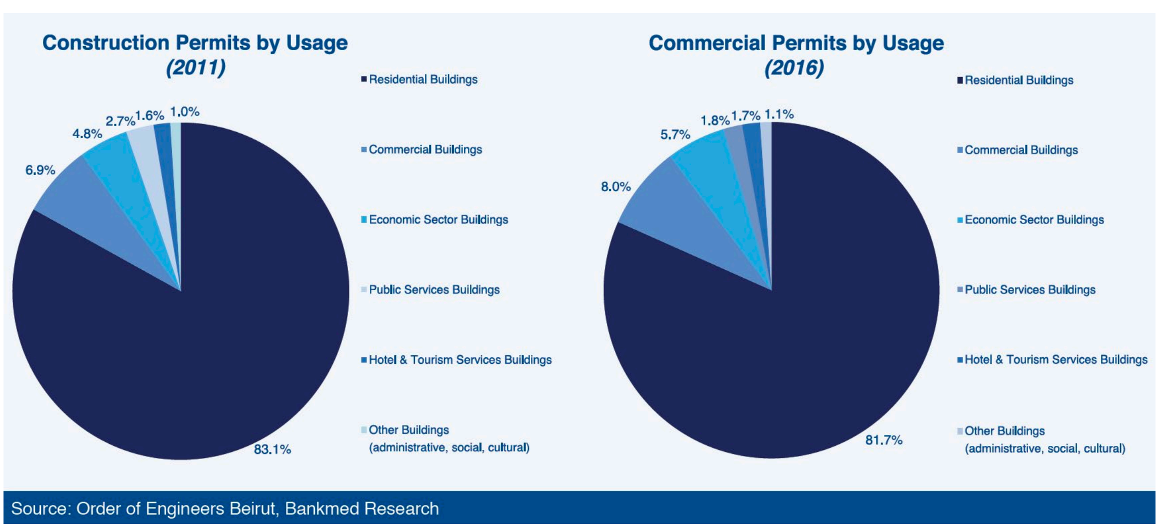

Figure 41. Analysis of Lebanon’s Real Estate Sector (CAS, 2007)

The residential market in Lebanon consumes upwards of 30% of the total generated electricity, the largest amongst all other sectors. Home sizes in Lebanon are amongst the highest when compared to regional counterparts (Figure 42). Similarly, household size in Lebanon is amongst the highest as well. This is indicative of a family structure, whereby, households occupy their home for longer periods of time and through multiple generations (Figure 43). Residential energy consumption constitutes the largest percentage of energy end use in Lebanon and is the highest when compared to regional counterparts (Figure 44). Hence, the benefits of adopting energy conservation measures (ECMs) are immense and could have significant yields. Lebanese households typically consume a large amount of electricity in comparison to other countries, attributed mainly to socio-cultural behavioural habits and norms such as cooking, watching TV, and air conditioning (Figure 45). Residential Energy Use Intensity (EUI) in Lebanon is relatively high compared to regional counterparts, especially countries with similar climate (Figure 46). Home and household sizes are probably contributing factors, in addition to lack of thermal insulation as well as cultural behavioural patterns and practices. However, lack of energy conservation measures and inefficient appliances are also major factors in increasing residential energy. To that end, the annual consumption of a multi-family residential building in Beirut was found to range between 178 kWh/m^2/yr and 220 kWh/m^2/yr (Ghaddar, 1998). A survey analysis study estimated residential EUI consumption at 135 kWh/m^2/yr (MEDENER, 2014). Another survey found annual consumption of a typical multi-story residential building around 148 kWh/m^2/yr (Mortada, 2018). An average EUI of 184 kWh/m^2/yr was generated based on existing data for purpose of the study. A survey of 500 households found average annual energy consumption at 6907 kWh and 1727 kWh per capita (Houri

& Korfali, 2005), placing Lebanon among the highest consumers of electricity compared to regional countries with similar climate. The average electric power consumption per capita jumped to 2,588 kWh in 2014 (OECD/IEA, 2014). Lebanon's EUI is significantly higher than several of its regional counterpart, emblematic of the existing building practices and energy consumption patterns. Home and household sizes are contributing factors, in addition to lack of thermal insulation as well as cultural behavioural patterns and practices. Electricity consumption per Lebanese household increased over 4% per year between 2000 and 2010 primarily due to growth in equipment usage (TV, refrigerators, ovens, air conditioning, ICT, water heaters, etc.) (MEDENER, 2017).

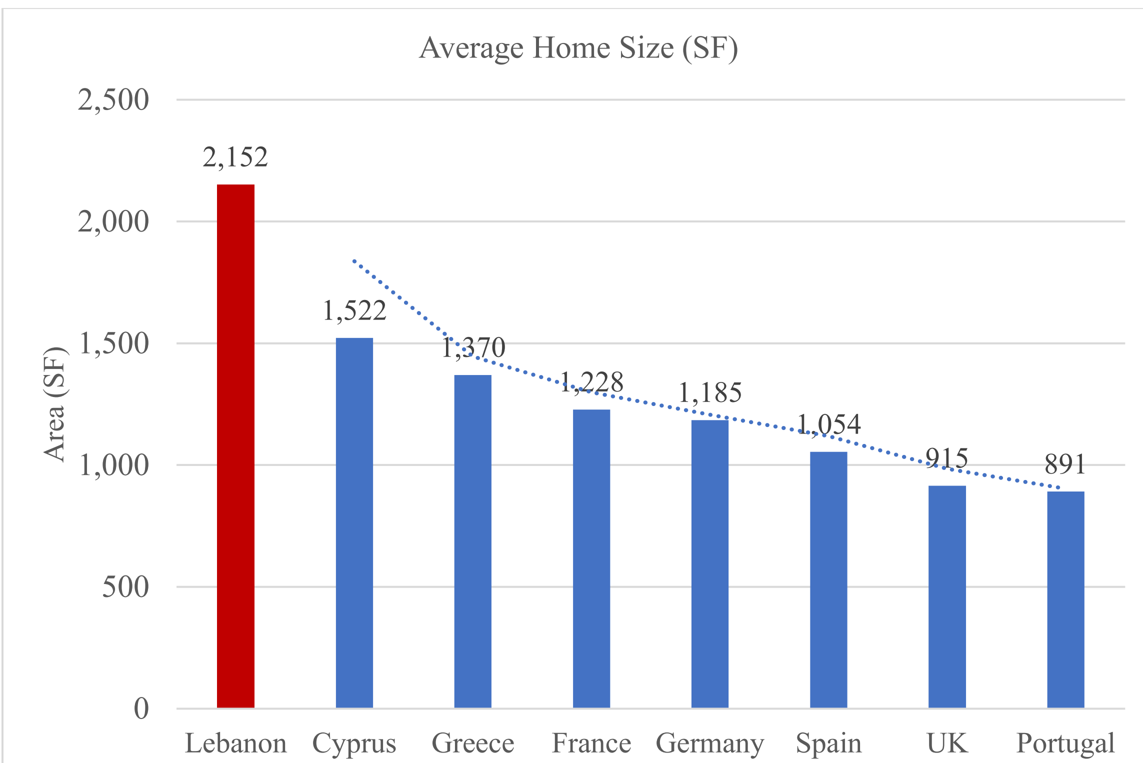

Figure 42. Average home size in Lebanon and regional counterparts (Odyssee-Mure, 2020)

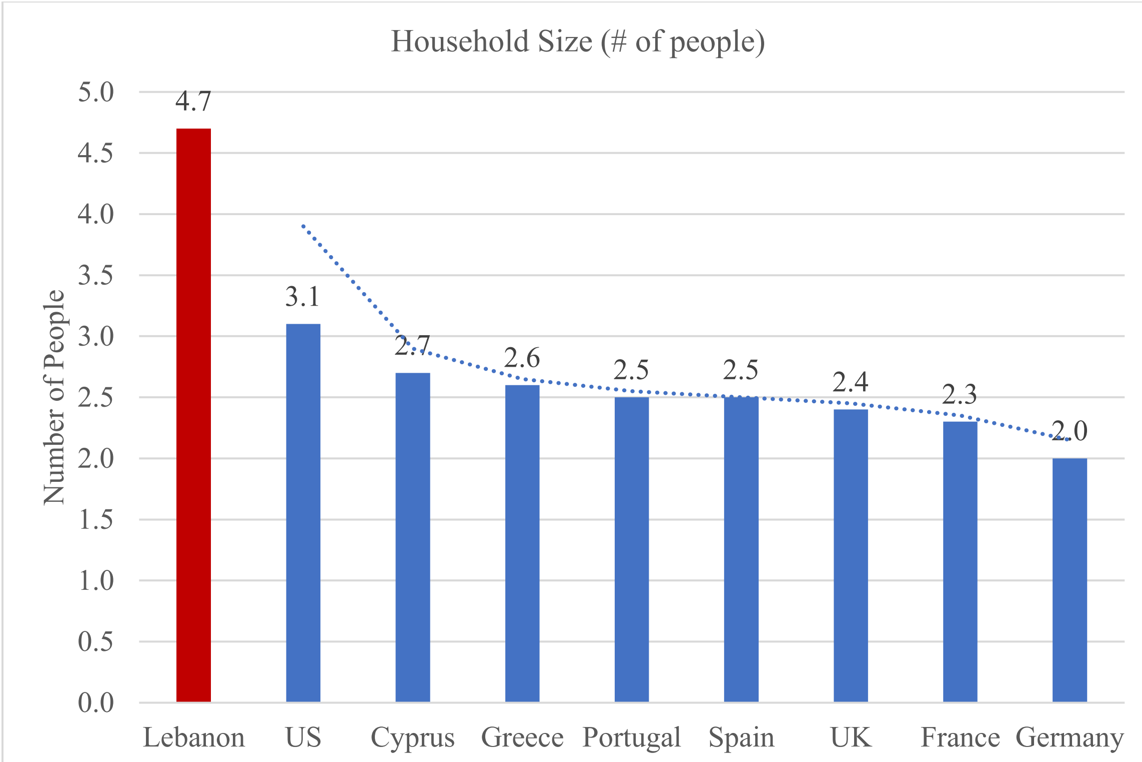

Figure 43. Average household size in Lebanon and regional counterparts (Odyssee-Mure, 2020)

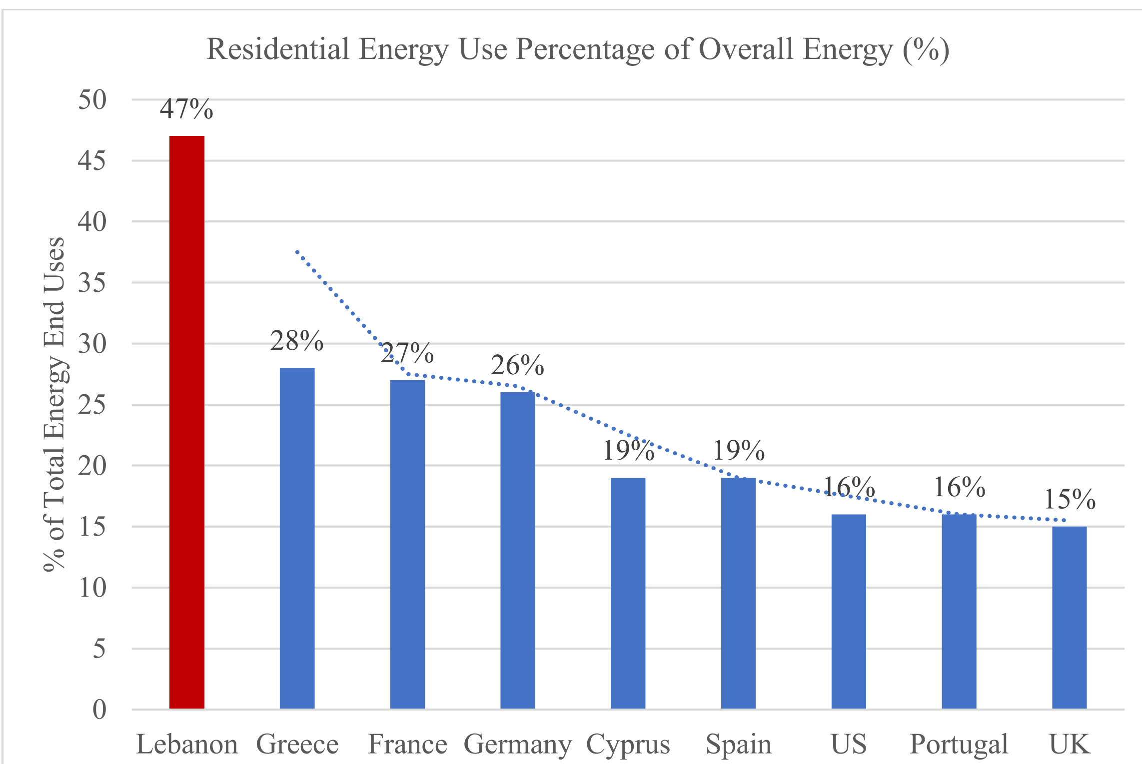

Figure 44. Residential energy use percentage of overall energy comparison chart (Odyssee-Mure, 2020)

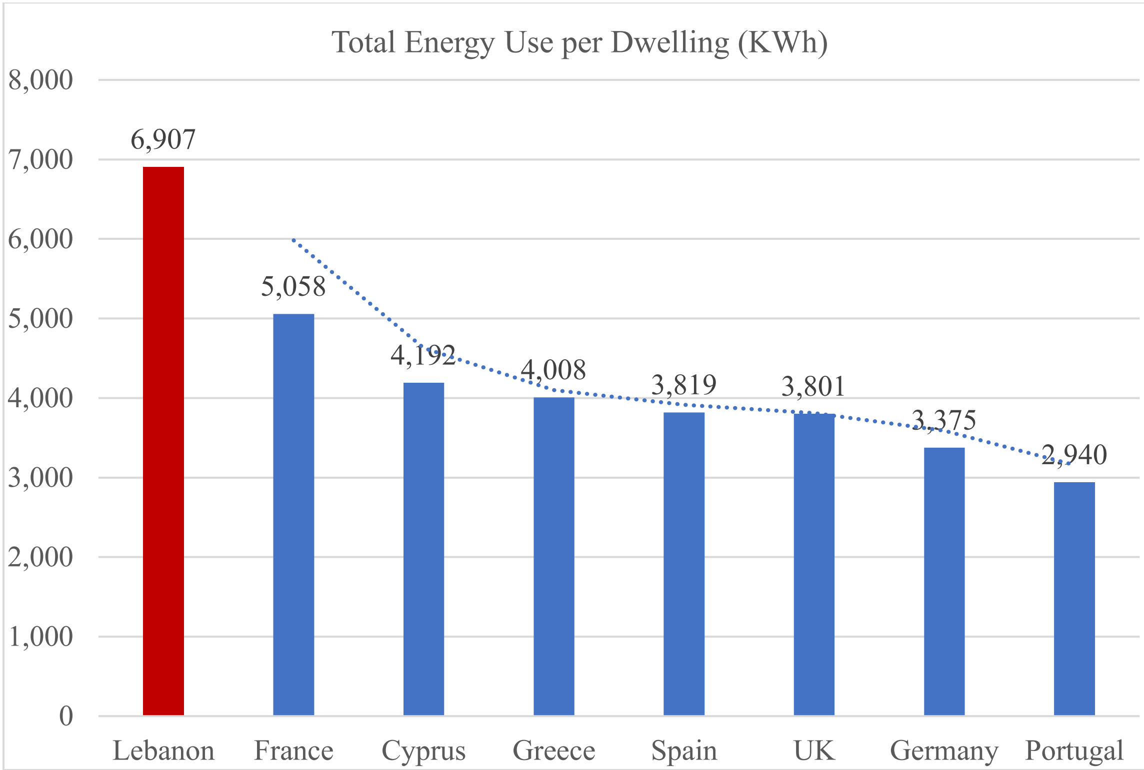

Figure 45. Total Energy Use per Dwelling in Lebanon and regional counterparts (Odyssee-Mure, 2020)

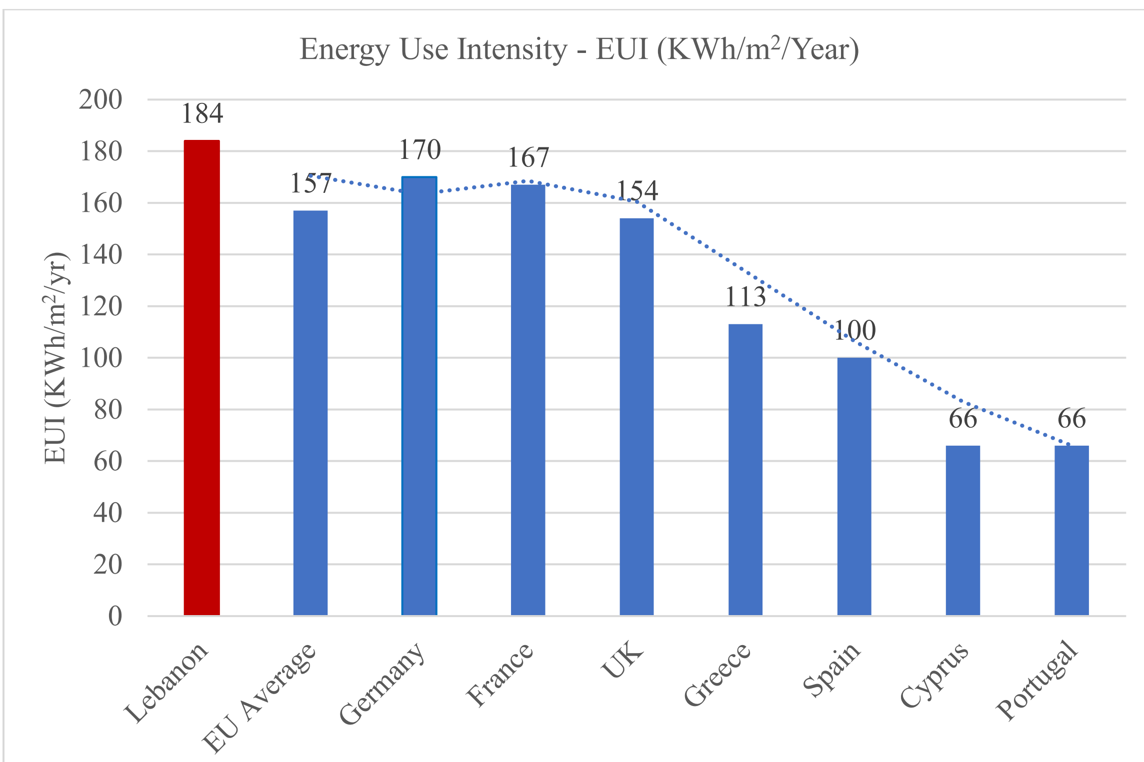

Figure 46. EUI of Lebanese residences compared to regional counterparts (Odyssee-Mure, 2020)

1.1.7 Assessment of Lebanon's Green Building Policies and Measures

Lebanon's sustainable building construction sector has lagged for many years. The 15-year civil war significantly damaged the nation's economy, infrastructure, and environment. Moreover, the country has been plagued for the past 20 years with power outages due to an outdated and unreliable energy sector. Nonetheless, Lebanon is an energy intensive country, exceeding many of its neighboring southern Mediterranean counterparts. To that end, energy consumption patterns have been increasing over the past decade and are projected to continue to grow over the next 10 years (World Energy Council, 2016). Lebanon imports more than 90% of the fuel it needs for its primary energy demand, mainly petroleum-based products. The heavy dependency on foreign fuel sources paired with unreliable and outdated energy production systems has drastically impacted socio-economic and environmental conditions. The civil war also left its mark on the building construction industry. The decade long conflict enhanced the proliferation of unregulated energy and unpermitted building practices. The result is a chaotic web of endless power lines intermingled with make-shift unsustainable buildings. The building industry consumes approximately between 45% and 75% of total electricity generation. The residential sector represents a significant portion of that demand, amounting for approximately 30% of total energy end-use consumption in Lebanon (Yathreb, 2016), constituting the largest amount amongst all other sectors. The premise of sustainable construction is still relatively unknown and untapped. As a result, the slow proliferation of green construction methodologies within the residential sector have had a major impact on energy consumption trends as well as air pollution. To that end, the role of both governmental and non-governmental agencies in promoting and advancing sustainable building construction is limited and in its infancy. Several public agencies such as the Ministry of Environment, Ministry of Industry, Ministry of Energy and Water, and the Council for Development and Reconstruction have introduced sustainability-driven measures and initiatives, funded by international agencies, aimed at promoting sustainable energy policies in Lebanon. Similarly, the Order of Engineers and Architects developed and published in 2010 a Thermal Standard for Buildings in Lebanon. However, most of these initiatives remained voluntary and non-enforceable, resulting in an intermittent and very slow adoption, if any, and without any significant impacts. Furthermore, lack of incentives for green construction paired with un-enforceable legislative regulations have been major obstacles in the adoption of green building codes. Additionally, the construction law does not take into consideration environmental impacts of construction and design practices in buildings. Nonetheless, Lebanese building code offers marginal guidelines for promoting and implementing sustainable construction. For example, a 2002 Environmental law No.444, encouraging the implementation of building Environmental Impact Assessments remained voluntary and hence, sporadically adopted and used (Awwad E. K., 2012). A thermal energy standard exists for buildings in Lebanon with the support of the ADEME of France. However, its voluntary. Thermal insulation standards were also introduced and made public but never adopted and remain primarily voluntary (EL Andaloussi, 2011). To that end, The Lebanese construction law is providing economic incentives for voluntary thermal insulation of building. Consequently, energy efficiency measures and upgrades aren’t widely adopted due to the lack of proper legislation systems with adequate monitoring agencies for enforcing and monitoring green construction practices. Moreover, lack of public awareness and absence of robust energy conservation policies have had a detrimental impact on the proliferation of green residential construction in Lebanon. Most residential buildings are not properly insulated, and in some instance, not insulated at all (Yathreb, 2016). This is directly attributable to the fact that thermal insulation standards are voluntary in nature (Figure 47). Moreover, residential construction is primarily driven by aesthetics in lieu of performance. As a result, the adoption and implementation of residential sustainable green building upgrades have been very slow and, in some instances non-existent. This could be directly attributed to weak legislative and institutional frameworks, subsidies of energy prices, and absence of a comprehensive national energy strategy (Missaoui, 2012). Furthermore, lack of public awareness and educational programs have also contributed negatively to sustainable development and construction. A weak legislative and institutional framework, lack of enforcement mechanisms, absence of green construction legislation, subsidies of energy prices, and the absence of a national energy strategy have all contributed to a minimal adoption of energy efficiency measures and policies in the residential building sector (Mourtada, 2008). Furthermore, Political and economic instability is a disincentive to invest in sustainable initiatives.

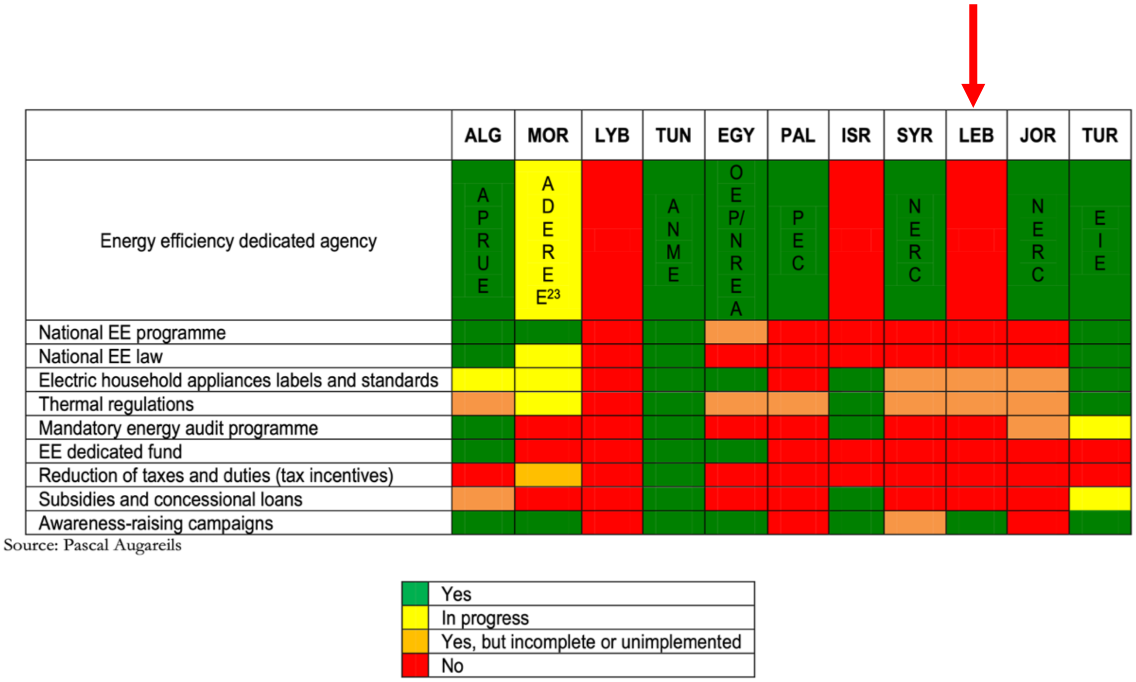

Figure 47. Energy efficiency measures in Mediterranean countries (EL Andaloussi, 2011).

1.1.7.1 Assessment of Lebanon's Sustainable Energy Indicators

In 2009, Lebanon pledged to reach 12% renewable energy target by 2020. To that end, a National Renewable Energy Action Plan was developed by the Ministry of Energy and Water (MEW) and Lebanese Center for Energy Conservation (LCEC). MEW published a policy paper for the electricity sector in 2010 providing a set of guidelines to begin the transition into renewable sources. At the same time, LCEC developed and published the National Energy Efficiency Action Plan for Lebanon (NEEAP). Both of these documents were aimed to transition Lebanon's from a fossil fuel dependent energy market to a more renewable and resilient path by 2015. Thereafter, MEW and LCEC published a new report, the National Renewable Energy Action Plan for the Republic of Lebanon (NREAP 2016-2020), as the main national document to prepare Lebanon to reach the 12% renewable energy target by the year 2020 via the adoption of a diverse set of renewable energy technologies (Lebanese Republic Ministry of Energy and Water, 2016). The MEW in collaboration with LCEC is trying to create a viable path for the proliferation of renewable energy in Lebanon by aligning all local and national efforts. Moreover, as a party to the UNFCCC (United Nations Framework Convention on Climate Change), the government of Lebanon alongside non-governmental organizations have initiated a process to apply strategies that could lead to reductions in GHGs. The country realizes the urgency of climate change challenges and have committed, on paper at least, to address those challenges in the context of a sustainable development framework. Nonetheless, Lebanon still suffers from serious environmental problems stemming from decades of neglect, lack of policies, and an absence of a legislative framework to encourage, incentivize, and enforce various initiatives. To that end, "Lebanon's Regulatory Indicator for Sustainable Energy" (RISE) 2019 score is 54 out of a 100, compared to the regional average of 66 (Figure 48 & 49). RISE is a platform developed by the World Bank to assess a country's policies and regulations in the energy sector organized by the three pillars of sustainable energy: energy access, energy efficiency, and renewable energy (World Bank, 2020).

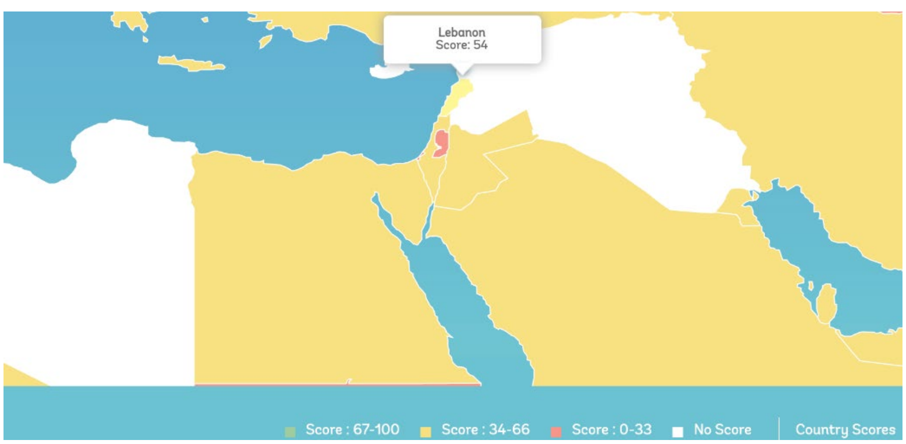

Figure 48. Map depicting Lebanon's RISE score (World Bank, 2020)

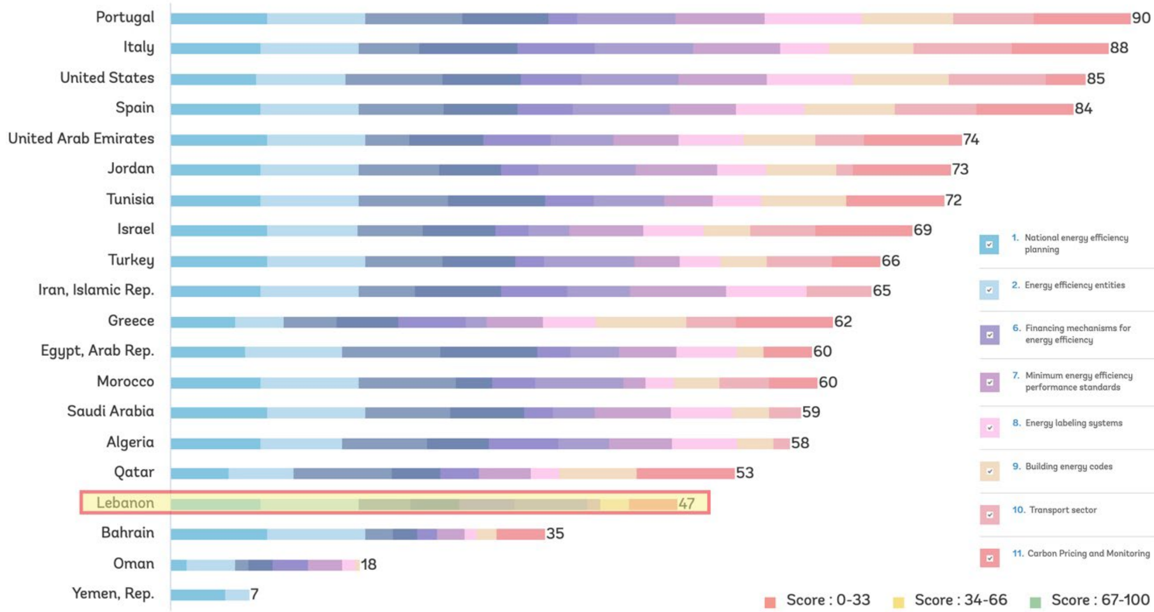

Figure 49. Lebanon's RISE scores in Energy Efficiency (out of 100) compared to others in 2019

Lebanon's overall low score is driven primarily by its energy efficiency and clean cooking pillars, scoring 47 out of 100 in Energy Efficiency in 2019 (Figure 50 & 51). The country scored very low in the following energy efficiency indicators: incentives and mandates, minimum energy efficiency performance standards, energy labeling, building energy codes, transport sector, and carbon pricing and mentoring (Figure 50 & 51). A deeper look into the sub indicators of building energy codes for instance shows that energy efficiency codes don't exist for new residential buildings. Moreover, there are no building energy standards as well. Similarly, no minimum energy performance standards or energy labeling have been adopted for HVAC systems. Moreover, 0% of the population had access to clean cooking in 2018 according to the World Health Organization. To that end, Lebanon ic completely devoid of any clean cooking standards encompassing efficiency, emissions, and safety. This is significant given the socio-cultural role cooking occupies in the behavior of Lebanese people and its role in society.

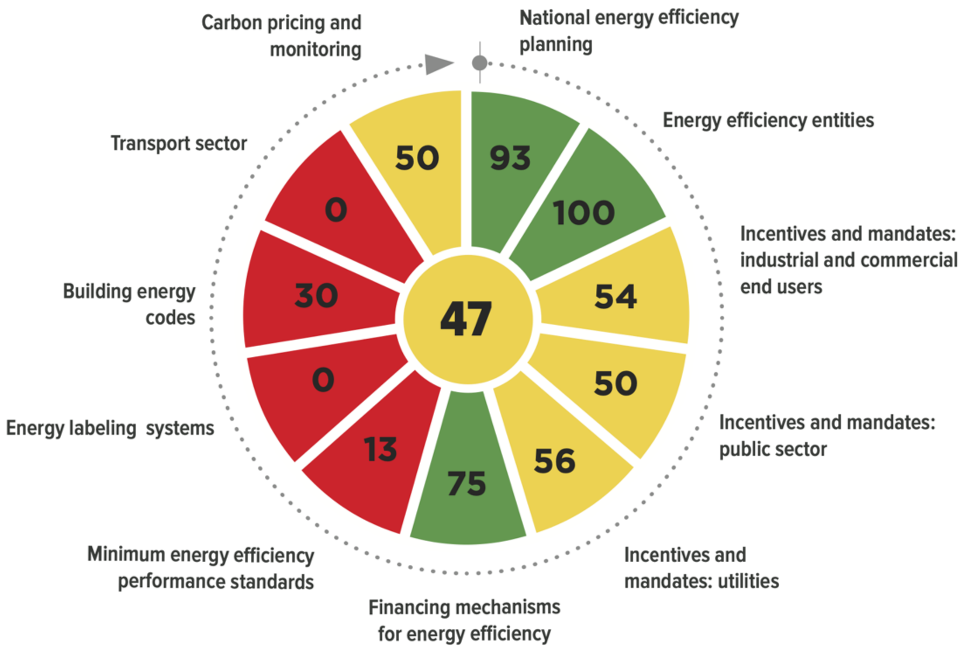

Figure 50. RISE scores for Lebanon's Energy Efficiency pillar (out of 100) in 2019

1	National energy efficiency planning	93
2	Energy efficiency entities	100
3	Incentives & mandates: Industrial and Commercial End users	54
4	Incentives & mandates: Public sector	50
5	Incentives & mandates: Utilities	56
6	Financing mechanisms for energy efficiency	75
7	Minimum energy efficiency performance standards	13
8	Energy labeling systems	0
9	Building energy codes	30
10	Transport sector	0
11	Carbon Pricing and Monitoring	50

Figure 51. RISE's Energy Efficiency indicators for Lebanon (World Bank, 2020)

Lebanon also ranks at the bottom in minimum energy performance standards when compared to neighboring countries and regional counterparts (Figure 52). Similarly, the country also is toward the bottom of the list when assessing the existence of building energy codes for new buildings (Figure 53).

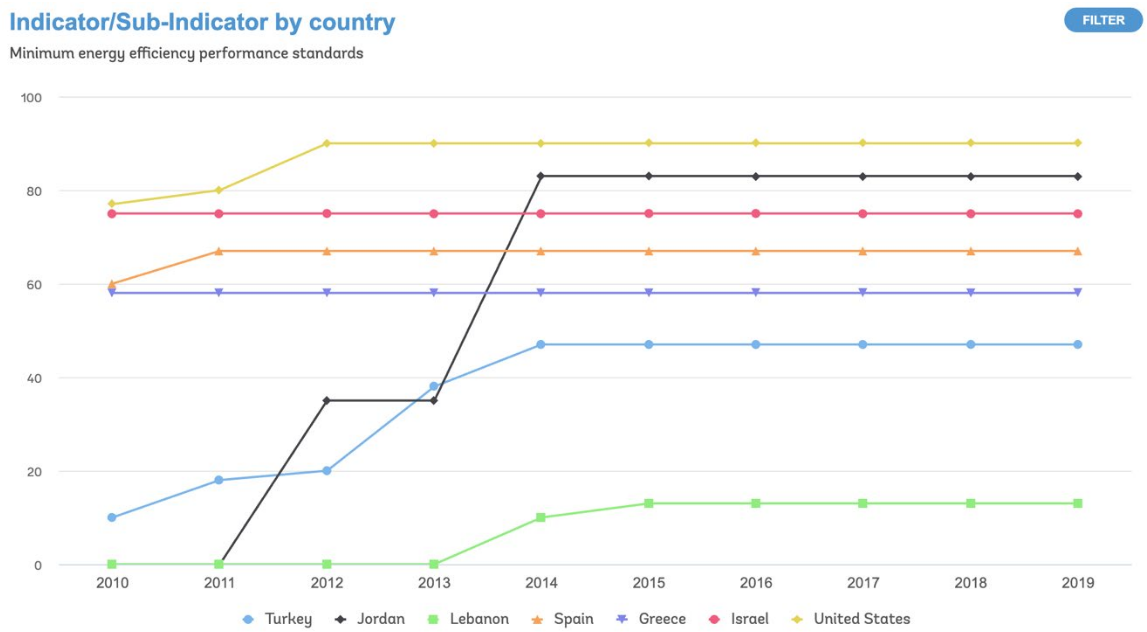

Figure 52. Comparison of minimum energy efficiency standards (World Bank, 2020)

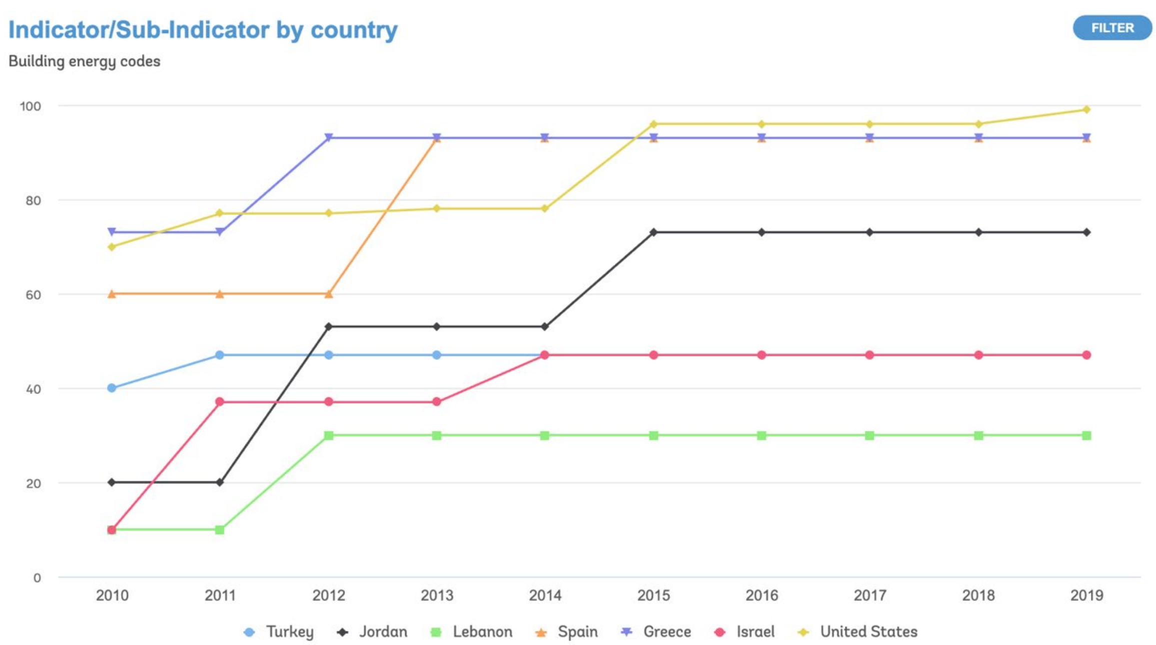

Figure 53. Comparison of availability of building energy codes (World Bank, 2020)

On the other hand, Lebanon’s renewable energy RISE scores are much higher at 67 out of 100 compared to 47 in energy efficiency. The country scored very well in the following renewable energy indicators: legal frameworks, planning for renewable energy expansion, and incentives and regulatory support (Figure 54).

Figure 54. RISE’s Renewable Energy indicators for Lebanon (World Bank, 2020)

Investments in renewable energy are slowly but steadily on the rise in Lebanon. A 2019 report by the Lebanese Center for Energy Conservation shows that 2.28% of the nation’s electricity was generated through hydropower in 2018. Photovoltaic power accounted for 0.55% in the same year, up from 0.26% in 2016 (Figure 55). Cumulatively, electricity generation from renewable energy amounted to 3.35% of Lebanon’s total electrical generation. Three wind farms at a capacity of 220 MW are scheduled to begin operation and generation by the end of 202. Furthermore, more than 21,000 solar hot water heaters were installed in 2015, reducing electricity demand by 61,992 MWh for the same year (MEW, 2020). Solar hot water heaters are the most established and installed renewable energy technology in Lebanon. The Ministry of Energy and Water also launched in 2011 an initiative to distribute three million CFLs to 1.5 million households. Solar PV installation also experienced steady growth in 2015 with the addition of 875 solar PV home systems in host communities and 178 PV installation (3.4 MW equivalent) in the private sector. In total, solar PV installed capacity reached 56 MWp with a generating capacity of 83,595 MWh in 2018, accounting for 0.55% of total generation (Farhat, 2019) (Figure 56 & 57). Residential sector PV installation amounted for approximately 16% of the total installed capacity in 2018.

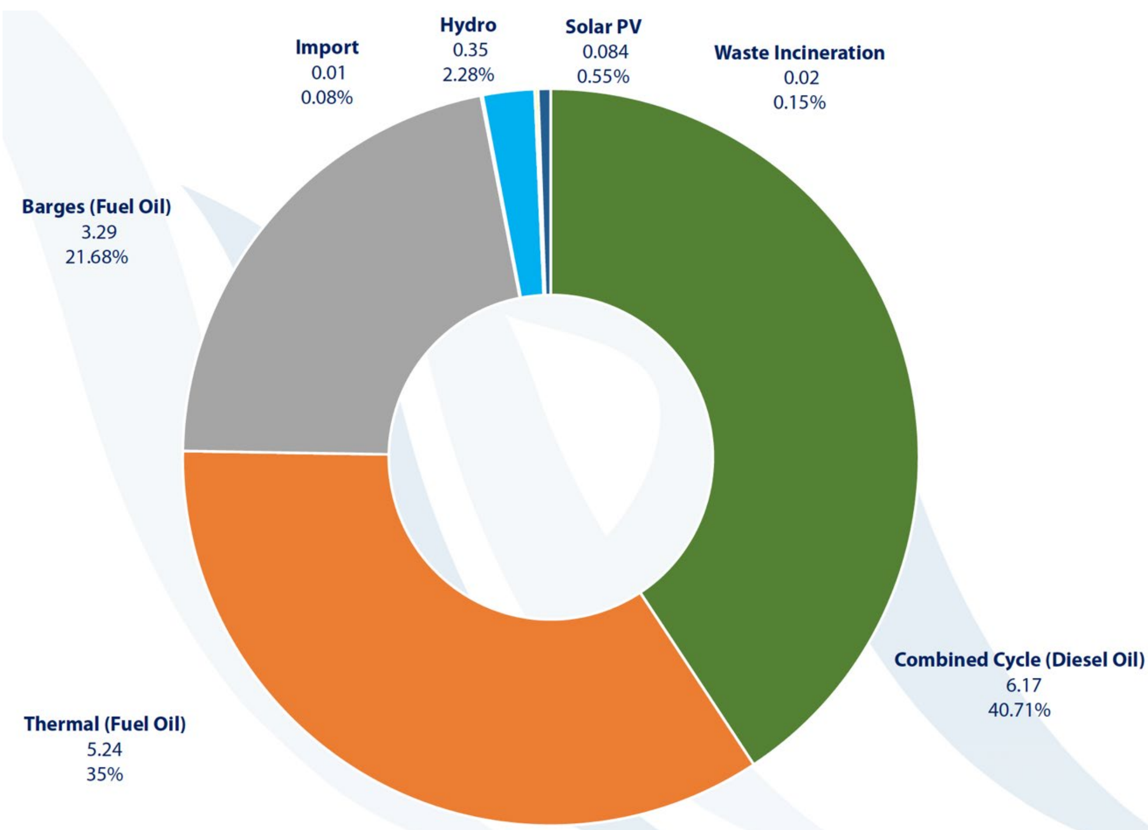

Figure 55. Lebanon's 2018 electricity generation (TWh)

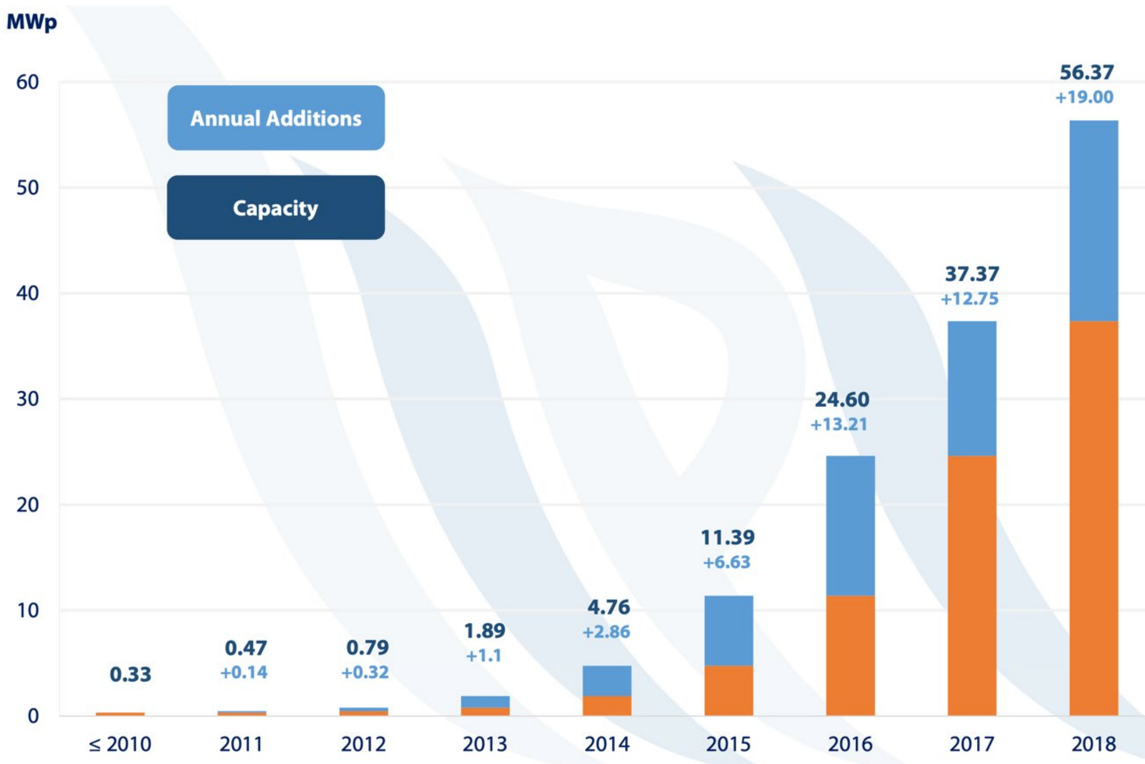

Figure 56. Solar capacity and annual additions in Lebanon (UNDP, 2019)

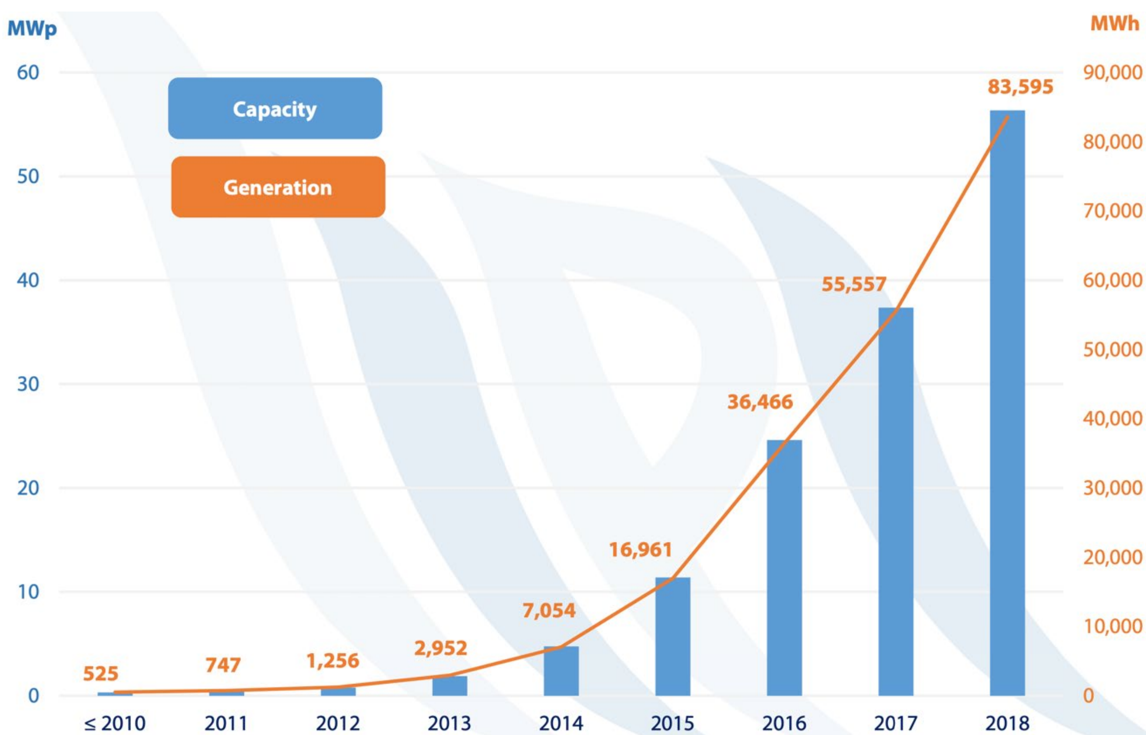

Figure 57. Solar PV capacity and generation in Lebanon (UNDP, 2019)

1.1.8 Conclusions

Energy production and consumption patterns are highly vulnerable to market forces and geo-political conditions. Energy consumption is also steadily increasing, while generating capacity remains deficient and unable to meet domestic energy needs. Similarly, power shortages are prevalent and widespread. The impact of an unreliable energy and electricity market has a significant effect on economic, social, and environmental conditions in Lebanon. Furthermore, antiquated fossil fuel thermal power plants paired with a primitive residential building sector have intensified environmental degradation and air pollution problems. Hence, the health and well-being of residents is at stake. The next section will outline the existing knowledge gaps within the residential energy performance sector, as well as explore the primary barriers to advancing energy conservation and efficiency efforts in Lebanon.

Bridging the Gap

It is evident that energy conservation measures are paramount to achieving desired levels of high performance within the Lebanese residential building industry, however, it is still uncertain what permutations are most effective in residential structures in climate locations such as Lebanon. A recent report showed that 84% of surveyed homeowners could not describe what entails an energy efficient building (Vaughan, 2017). The report also concluded that there is a lack of attention on the adoption of robust optimal solutions within the residential building industry. Similarly, little attention is devoted to the impact of design configurations on energy use. Indeed, building design is a significant unknown variable as it relates to residential energy consumption. Buildings represent very complex environments, encompassing many moving parts and variables. Therefore, it is imperative that any research be focused on a holistic investigation of all parts and systems parametrically, in an integrated, iterative, and analytical manner. The research will encompass a comprehensive impact analysis of various architectural metrics evaluating their effect on energy performance. The following section will present an overview of the state of existing literature on energy use and efficiency in the residential building sector.

1.1.9 Research on Residential Energy Consumption

Literature clearly indicates a strong correlation between green building features and energy performance (Smeds, 2007). Studies have shown that certain building upgrades, encompassing HVAC systems, envelope construction, glazing, and insulation, have a significant impact on various building energy end uses such as heating, cooling, lighting, and hot water (Christensen & Norton, 2008). Energy implications of varying architectural building system indictors have been thoroughly investigated by prior research (DOE, 2016). However, many studies have failed to assess the impact of targeted permutations of such indictors on energy use in residential apartment buildings. Most of the existing research focuses either on the impact of singular energy conservation measures or a cumulative-all-included-approach (Logue, 2013). For example, a 2006 study of energy efficient houses in Denmark highlighted measurable reductions in energy use when applying an all-inclusive approach of building system upgrades. The study measured significant improvements in energy performance when upgrading the following systems: HVAC, insulation, ventilation, glazing, and lighting (Tommerup, Rose, & Svendsen, 2007). Similarly, a Swedish study found considerable improvements in energy use via a cumulative-based approach employing building systems upgrades in insulation, building envelope, windows, and air tightness (Smeds, 2007). Another study successfully evaluated the feasibility of energy-efficient design in Vermont, while utilizing energy conservation measures encompassing windows, air/vapor barriers, insulation, ventilation, and HVAC systems (Maclay, 2015).

While it is prudent to investigate the impact of all building systems on energy consumption, it's imperative to examine the most optimal permutations correlating to energy efficiency. Existing literature and research have not robustly analyzed the effects of optimal combinations of building system upgrades in an iterative parametric approach in the Lebanese residential market. Correspondingly, there's a significant knowledge gap in assessing the efficacy of select targeted combinations of upgrades on residential energy consumption in Lebanese apartment buildings. In addition to the lack of robust research on the impact of targeted permutations of building system upgrades, there has not been extensive data on the impact of varying building design configurations on energy performance in residential buildings. For example, building geometry, footprint, and shape are often neglected as energy performance indicators. Most studies have focused on the effect of building system upgrades on overall energy use, while few have examined the impact of architectural design configuration variances on residential energy consumption (Krem, Hoque, Arwade, & Breña, 2013). Furthermore, there isn't robust literature pointing to a clear correlation between building morphology and energy performance. However, building science research does imply a connection between geometry of a structure and energy transmission (NREL, 2011). Building construction and design configuration variables such as "area to volume ratio" are closely related to thermal losses in residential buildings. In a study of multi-family residential structures in Turkey, Erlalelitepe (2011) found a noteworthy correlation between design configuration and energy saving potential. Similarly, another study concluded that a correlation does exist between envelope design and energy use in residential buildings (Granadeiro, Duarte, Correia, & Leal, 2013a). However, these authors indicated that energy modeling and performance information is usually absent during the early stages of design, where a building envelope is defined and shaped. The researchers concluded that it is imperative upon designers and building professionals to thoroughly investigate the impacts of architectural design variances early during the design stages. The study also recommends more resources slated toward investigating building envelope's architectural shape and its correlation to energy performance optimization. Regardless, it remains unclear to what extent varying design configurations would impact energy use in residential structures within the targeted region of this study. Furthermore, the impact of building design on energy consumption is relatively unknown when paired with building system upgrades. The next section outlines existing research entailing the impact of targeted architectural variables on energy consumption and efficiency.

1.1.10 Impact of Targeted Architectural Variables on Energy Use

Architectural building systems play a significant role in determining the outlook of a building's energy performance. Most research to date has focused on the impacts of building system upgrades on energy use in residential buildings, often neglecting to assess building design variables such as massing and form. Furthermore, research shows that the majority of efforts have been directed towards either singular energy conservation measures or an all-inclusive approach, overlooking targeted optimal green building upgrades. Nonetheless, findings from these types of studies point to three primary indicators impacting energy performance and demand in residential buildings: super-insulated envelopes, high-performance glazing system, and high efficiency mechanical heating and cooling (Parker, 2008). The following section will explore various green building upgrades and their impact on residential energy consumption.

Singular Upgrade – Thermal Envelope. A building envelope comprising the roof, walls, foundation, and glazing usually accounts for 35-40% of a home's overall energy demand (DOE, 2016). A home's envelope acts as a thermal barrier that plays a critical role in regulating interior temperatures and overall energy use, hence, impacting over thermal comfort and energy demand. A properly insulated and sealed building envelope has the potential to impact approximately 50% of building energy loads (NREL, 2011). For example, an average home in the northeast region of the Unites States could realize a 12% reduction in total energy use and a 19% reduction in heating loads by properly sealing air leaks and adding more insulation (Center for Climate and Energy Solutions, 2017). Moreover, properly insulated and sealed roofs could save homeowners 10-15% in peak heating and cooling demands. Properly air-sealed building envelopes tend to yield 20-30% reductions in heating demand (International Energy Agency, 2013). Department of Energy data shows a 10% reduction in total annual energy expenditures and 20% savings in cooling and heating costs via properly insulated and sealed building envelope (DOE, 2016). To that end, building envelope systems such as structural insulated panels (SIPs) and insulated concrete forms (ICFs) have been shown to reduce overall energy demand by up to 30-40% (NAHB, 2006). Furthermore, super-insulated building envelopes such as double-stud construction tend to reduce between 20-30% of energy demands in colder climate locations

(EIA, 2017). For example, insulation as a singular energy conservation measure have been shown to yield energy reductions between 10 and 25% depending on location and climate (Anderson & Christensen, 2006). A study of residential structures in mild to cold climates in the U.S. found 10-15% reductions in annual heating loads when upgrading the thermal resistance of a home's building envelope via upgraded insulation levels (Park, SrubarIII, & Krarti, 2015). A Rutgers University study analyzing single-family homes in New Jersey revealed 27% energy savings with the application of advanced framing and upgraded insulation (The Rutgers Center for Green Building, 2011). In a study of a hypothetical residential building in Sydney, the researchers were able to show energy reductions between 15-25% via upgraded insulation levels across the envelope (Tabrizi, Hill, & Aitchison, 2016).

Singular Upgrade – Glazing Systems. Considered one of the weakest points in a building envelope, windows are critical components in a comprehensive energy efficiency strategy. Windows consume approximately 24% of a building thermal energy loads, 19% for heating and 39% for cooling (Arasteh, Selkowitz, & Apte, 2006). Heat energy transmission through glazing systems plays a key role in determining energy demand and overall thermal comfort in residential buildings. Optimal high-performance glazing systems have the potential to reduce residential energy consumption by 10-50%, depending on application and location (Ander, 2016). Department of Energy data shows 7-24% annual energy reduction by using Energy Star rated windows (DOE, 2016). Studies by the Center of Climate and Energy Solutions echo these findings and have been able to demonstrate 10-50% reduction in energy consumption based on optimal glazing specifications and window design (Center for Climate and Energy Solutions, 2017). Key to these findings are three parameters: placement, surface area, and performance specifications. To that end, studies of homes in the northeastern United States have shown a potential 6-10% reduction in energy use when upgrading to double-pane low emissivity windows (The Rutgers Center for Green Building, 2011). Other pilot projects have demonstrated 20-25% reductions in cooling loads and peak electrical loads with proper window placement and specification (International Energy Agency, 2013). Window to wall ratio (WWR) percentage is another key factor in determining the impact of glazing systems on energy use. Studies have shown the potential to double energy savings by decreasing a façade's WWR in hot climate locations (Ihm, Park, Krarti, & Seo, 2012), reducing annual cooling loads by 25-35%.

Singular Upgrade - HVAC Systems. Space conditioning end-uses such as cooling and heating loads account for approximately 50% of the energy consumed in an average household (DOE, 2016). In Lebanon, cooling loads constitute the majority of a home's energy end-uses. The DOE estimates 30% savings in energy consumption with upgraded HVAC equipment coupled with appropriate insulation and air sealing (DOE, 2016). For example, Energy Star rated air conditioners are 10-15% more efficient than standard models (DOE, 2016). Moreover, it is estimated that geothermal heat pump systems could reduce a home's energy use by 30-60%. Studies have shown energy saving potential between 14 and 45% when upgrading residential HVAC systems (The Rutgers Center for Green Building, 2011). Furthermore, 37% reductions in annual energy operating costs could be achieved with high level efficient active mechanical systems. The second largest energy user in a house is water heating consuming 18% of total energy end-uses. DOE

(2016) research has demonstrated energy savings between 30-50% when comparing efficient upgraded water heaters with standard units.

Multiple-paired Upgrades. The impact of singular energy conservation measures is well documented. However, the impact of multiple-paired architectural variables, incorporating building systems and design configuration, on energy consumption in residential buildings remains somewhat deficient (Yılmaz, 2007). Nonetheless, studies evaluating the impact of multiple building upgrades have shown a significant effect on energy consumption in residential buildings. For example, various residential blocks in Eastern Europe measured between 67.8% and 77.2% energy saving potential when upgrading envelope insulation and window U-values (Csoknyaia et al., 2016). Varying exterior wall insulation levels and window R-values were found to have a significant impact on energy use, specifically reducing heating and cooling loads (Croitorua, Nastasea, Sandua, & Lungu, 2016). This study also discovered 40% improvements in energy use by optimizing building orientation. Orienting a house facing south was found to be very effective in reducing energy demand in cold climates, especially heating loads. However, the researchers concluded that improving thermal resistance of both exterior walls and windows was the most optimal approach to reduce overall energy consumption. Similarly, high energy performance in Turkish residential buildings was correlated with optimal east-west axis orientation (Kazanasmaza, Uygun, Akkurt, Turhan, & Ekmenc, 2014). The study also found that lower ratios of external surface areas to net usable floor area yielded higher energy savings. A parametric study integrating nine different simulated building geometries, assessing building footprint, shape, and volume, showed a noteworthy association between building shape and energy demand (Granadeiro et al., 2013a). Findings revealed a 28% reduction in energy loads (heating & cooling) with design iterations that had lower ratios of external surface areas to net usable floor areas. Window areas percentages and envelope insulation levels were primary drivers of energy consumption in a hypothetical study analyzing 8000 variations of a hypothetical residential building designs (Granadeiro et al., 2013b). The researchers showed a strong statistical correlation between building envelope upgrades, aimed at increasing thermal resistance and minimizing heat transfer, and overall energy demand. A study of newly constructed homes in Mexico showed 52% annual energy savings when adopting a combination of improved thermal insulation and efficient appliances (Griegoa, Krarti, & Hernández-Guerrero, 2012). Similarly, Danish researchers realized a 40% reduction in electricity consumption upon upgrading envelopes' thermal insulation and air tightness (Tommerup, Rose, & Svendsen, 2007). To that end, properly insulating a home coupled with effective air sealing have been shown to reduce energy use by 5% to 16 % depending on location (DOE, 2016). Moreover, utilizing a super-insulated envelope with virtually no leaks has yielded energy savings around 25% (DOE, 2016). Similarly, upgrading the R-value of attic insulation has resulted in a 15% reduction of a home's cooling and heating loads. It was also concluded that energy optimization is best enhanced when building envelope upgrades are sequentially selected first to be followed by HVAC upgrades, potentially yielding a 70% optimization rate (Bichiou & Krarti, 2011). Collectively, studies in warm climates have advocated the adoption of the following green building upgrades as primary energy indicators: high-performance HVAC systems, super-insulated envelope, high-performance glazing, and low percentage south-facing window to wall ratio. Adoption of these indicators into residential buildings have shown on average energy-use reductions between 40% and 60% (NREL, 2011). Alternatively, a large body of literature points to weak and insignificant statistical correlations between energy consumption in residential buildings and the following architectural features: architectural style and typology, interior floor and space layout, equipment and system schedules, doors specifications, and roof characteristics (DOE, 2016). In contrast, few studies have explored the correlation between architectural design variables (building footprint, shape, massing, volume, etc.) and energy use. Moreover, the impact of building design variables paired with optimal building systems has not been robustly investigated and evaluated, especially within the context of a Net Zero Energy framework. Furthermore, robust literature on energy performance in a typical Lebanese residential apartment building is severely deficient and, in most instances, completely non-existent. The next section will explore the various barriers to proliferation of Zero Energy Building efforts in Lebanon's residential building sector.

1.1.11 Energy Conservation & Zero Energy Buildings Efforts in Lebanon

Efforts to bring to mainstream the adoption and implementation of zero energy buildings in Lebanon have been initiated by groups such as the Lebanon Green Building Council (LGBC) and the Order of Engineers and Architects, albeit at a very slow pace. Furthermore, some research and studies have also explored and analyzed the impact of green building upgrades on energy consumption in residential buildings (YATHREB, 2016). To that end, interest in building energy performance has increased in Lebanon during the past decade. However, most of the studies have focused on commercial applications. Residential buildings accounted at the high end about 47% of total energy consumption in Lebanon (YATHREB, 2016). It's therefore imperative to robustly investigate the impact of multi-criteria building upgrades (design + systems) on energy consumption in a standard apartment block. Efforts of moving the residential construction industry towards a Zero Energy approach have been extremely slow and, in most cases, absent from the Lebanese market. Most efforts have been limited to academic research and non-governmental agencies, such as the Lebanese Center for Energy Conservation (LCEC). To that end a 2019 study evaluating the applicability of Zero Energy buildings in Lebanon did show a feasible approach towards the adoption of such buildings utilizing three pillars: energy systems upgrades, material properties, and occupant socio-cultural behavior. The study also revealed that energy consumption in Lebanon is heavily dependent on the three following components: lighting, TV/equipment, and the kitchen (Omar, 2020). Another study evaluating the feasibility of Zero Energy buildings in Lebanon concluded that heavy weight double masonry walls produced the least amount of interior overheating. The authors argued that heavy weight envelope construction is the most efficient typology, when considering Lebanon's climate and its overreliance on air-conditioning to achieve thermal comfort during summertime (Saleh, 2018). The author of another study evaluated optimal designs for Net Zero Energy buildings in Lebanon and provided a roadmap to promote and develop a wide understanding of Net Zero Energy design concepts (Harkouss, 2018). Despite the various studies mentioned above, Zero Energy Building efforts remain primitive in Lebanon's residential market. Furthermore, the adoption of green building upgrades is also lacking. The following three barriers could be identified as the primary drivers of the energy performance gap in the Lebanese residential market: financial, informational, and behavioral barriers. Economic issues, cost factors, and lack of incentives account as the main financial barriers. Lack of information, tools, and access to data constitute the informational barrier. Preconceived notions of green upgrades and energy efficiency coupled with socio-cultural habits and norms entail the last and most difficult category, behavioral barriers. Furthermore, the proliferation of energy conservation efforts is also hindered by lack of public awareness, lack of enforcement mechanisms for voluntary initiatives, lack of legislative policy for green construction and energy conservation, and most significantly, the ongoing chronic political and socio-economic instability plaguing the country for the past decades.

1.1.12 Barriers and Challenges to Energy Efficiency

Efforts to bring to bear energy efficiency investments in Lebanon have been challenging and slow at best, especially in the residential building market. To date, most energy conservation and efficiency measures remain largely voluntary and non-enforceable. As a result, the Lebanese housing sector has struggled to improve its overall energy performance and outlook. The residential building sector is one of the largest consumers of energy and electricity in the country, accounting for approximately 30 to 40% of total generated energy. This lag in energy efficiency is primarily due to weak legislative policies and frameworks, lack of enforcement mechanisms, absence of green construction legislation, subsidies of energy prices, and unawareness of energy consumption patterns. Hence, energy efficiency investments and interventions are intermittent and sporadic. The following are some of the primary barriers to energy conservation and efficiency proliferation in Lebanon:

Technology Barriers. To achieve optimal reductions in energy consumption and associated emissions, innovative and best technology practices must be employed to achieve desired results. However, such technologies and practices are often not widely or viably available in countries like Lebanon with transitioning economies and politically unstable conditions. Furthermore, technological advancements are often limited to private endeavors and remain largely unsupported.

Economic Barriers. Lebanon's dire economic conditions have plagued the nation for decades, causing severe financial stress on its citizens and organizations. As a result, environmental issues including energy use and associated pollution often takes a back seat to more urgent and pressing economic conditions affecting livelihoods. Furthermore, lack of financing and access to capital makes it extremely difficult for homeowners and tenants to invest in energy upgrades. To that end, commercial lending and financing have not been involved in the energy efficiency market yet. Most commercial banks are not aware or willing to offer loans to individuals or associations for energy investments.

Energy Access and Cost Barriers. Lebanon's energy market is heavily subsidized and hence energy prices are kept artificially low. However, production shortfalls plague the energy generation system where demand is not met. As a result, Lebanese pay two energy bills, public and private. The low energy prices and subsidized tariffs have led to severe budget shortfalls and debt, causing a massive inflation in national debt. The result is an unreliable power grid afflicted by frequent outages and blackouts. Access to reliable energy and electricity remains a huge problem in the country, causing massive energy inequity and poverty. Furthermore, the artificial low energy prices don't take into consideration the environmental costs of fossil fuel generated electricity as well the financial burdens of infrastructure and capital costs.

Social Barriers. Residential energy use is heavily dependent and affected by behavior and consumption patterns. The lack of awareness of energy consumption patterns and waste is a significant barrier to energy efficiency investments and interventions. This behavior-related barrier is often the most difficult to overcome. Energy conservation is directly dependent on consumer behavior. However, most homeowners and tenants do not understand how energy is consumed. Moreover, there's is a lack of educational frameworks and platforms on energy consumption and conservation measures. As a result, Energy investment and efficiency campaigns are absent.

Political Barriers. Political commitment and will are critical drivers in advancing energy conservation and efficiency investments and interventions on a wide scale. Lebanon's unstable political situation is probably one of the most significant barriers to such investments. The lack of appropriate incentives, regulations, and enforceable legislative frameworks have hindered the propagation of energy efficiency investments. Furthermore, the governmental decision to regulate energy prices and keep them artificially low has led to high levels of energy consumption and waste. The absence of government-set robust performance-based building codes and standards have also been a major barrier. Building energy codes are key to establishing set benchmarks and parameters for energy use nationally. Lastly, energy-consumption public awareness campaigns are crucial to starting the discussion about energy efficiency and conservation. Unfortunately, the Lebanese government has been largely absent in this endeavor as well.

Zero Energy Building Case Studies

The proliferation of Zero Energy Buildings has sped up during the last decade, in part, due to a propagation of sustainable building-related policies and measures aimed at transforming the market towards a Zero Energy environment. For example, many EU countries have adopted Zero Energy policies and measures aimed at transitioning their building sectors and markets. Similarly, professional AEC organizations have also adopted initiatives such as the *2030 Challenge* to move the industry towards a Zero Energy/Emissions paradigm. Moreover, Zero Energy approach have also been adopted by many non-governmental organizations to promote and adopt the United Nation's *Sustainable Development* goals. As a result of these efforts, Zero Energy Buildings have increased in number and geographic distribution. However, most net zero energy developments encompass commercial buildings and single-family residential homes. Proliferation of net zero energy apartment buildings remain slow and isn't widely adopted yet. The following section will present a series of case studies from around the world to further explore Zero Energy projects including apartment buildings, where available, and single-family homes (Appendix B).

USA – Hanover Olympic

Hanover Olympic Apartment building is the first solar powered net zero energy apartment building in Los Angeles, California (Figure 58). A super-insulated airtight building envelope was employed to minimize energy loads and maximize efficiency. A 65KWp solar panel system generates approximately 90,000 KWh of electricity annually, more than the building consumes. Each of the 263 units features energy conservation and efficiency measures such as thermal isolation, high performance HVAC system, high performance glazing systems, LED lighting with occupancy sensors, Energy Star appliances, and state of the art equipment. 20 of the 263 units are completely solar powered and self-sustaining. Moreover, each unit is equipped with an iPad Mini energy tracker to allow tenants to track and monitor their energy consumption and solar generation.

Figure 58. Exterior image of the Hanover Olympic Apartments in California (Google Images)

USA – 303 Battery

303 Battery is Seattle's first net zero energy high-rise apartment building (Figure 59). The 15-story development broke ground in 2021, spear headed by Sustainable Living Innovations, a Seattle tech company. The building features many sustainable strategies including radiant floor heating, optimal glazing for daylighting access, light sensors, smart thermostats, grey water recycling systems, rainwater harvesting, ecologically friendly building materials, and solar panels for on-site renewable energy production. The structure uses building integrated photovoltaic panels on the roof, exterior envelop, and balconies. A back of Lithium batteries are also planned for the basement level to provide electricity production at nighttime when solar is offline. The building is currently being certified by the International Living Future Institute, a global leader of Zero Energy initiatives and guidelines.

Figure 59. Exterior rendering of 303 Battery in Seattle (Google Images)

Germany – Schwaikheim Housing

The Schwaikheim Housing project located in rural Germany and constructed in 2019, was one of the first net zero energy apartment buildings in the country (Figure 60). It includes six apartments and a workshop. The building is made almost entirely from reusable and recycled materials. Some of the sustainable features include high performance glazing systems and building envelope, high performance heat pump, and solar panels mounted on the roof of the building. The building uses sustainably harvested local timber for most of its exterior finishes. All six apartments are south facing for optimal passive solar heat gain and daylighting.

Figure 60. Exterior image of Schwaikheim Housing project located in Germany (Google Images)

France – ZERO-PLUS

ZERO PLUS project in France is a social 18-apartment housing block located in Voreppe (Figure 61). The building employs energy efficient construction materials and products, combined with on-site renewable energy production for both electricity and heat. The project also uses a biomass district heating system for hot water heating. High performance windows, energy monitoring, and daylight controls and sensors were also used through the building. The project also utilized solar thermal cooling, hybrid heat and electricity generation, and multifunctional roof edge solar production. Altogether, the building produced more than 120 KWh/m^2/yr from the on-site photovoltaic system, offsetting its entire annual net energy consumption.

Figure 61. Exterior image of the ZERO-PLUS apartment building in France (Google Images)

Spain – Sea Container House

This Zero Energy house in Spain has earned an "A" rating in building energy performance and is Passivhaus Certified (Figure 62). The house is constructed utilizing reused shipping containers. To ensure high performance, the house is super insulated with both air and vapor barriers. To that end, the envelope was carefully designed to reduce thermal bridges to maximize energy efficiency. The building uses an alternative aerothermal heat pump for heating and hot water needs. It also employs a mechanical ventilation system for heat recovery. The house has ample natural light, hence minimizing the reliance on electricity. The house also uses efficient lighting, energy saving lamps with daylight sensors. It's also very well ventilated, reducing cooling loads. The building has an EUI of 6.3 KBtu/sf/yr.

Figure 62. Exterior image of the Sea Container House in Spain (Google Images)

Greece – The House Project

The house Project in Greece was renovated and converted to a Passivhaus Certified Zero Energy building in 2015 (Figure 63). The existing structure was originally built using reinforced concrete with no insulation in the walls. The building was completely thermally insulated and refurbished. The 3.5 KWp PV system generates more energy on average than the building consumes. 92% of the domestic hot water needs are provided by solar thermal panels mounted on the roof. The house also uses natural ventilation to provide cooling during the warmer month of the year. A heat recovery system is employed to maximize energy efficiency as well. The building was able to reduce its energy use intensity from 330 KWh/m^2/yr to 28.46 KWh/m^2/yr. The normalized energy use intensity was calculated at 9.2 KBtu/sf/yr.


Figure 63. Exterior image of the Passivistas House Project in Greece (Google Images)

Italy – Project Botticelli

The Zero Energy Project Botticelli in Sicily earned an "A" rating in building energy performance (Figure 64). The house is also Passivhaus Certified. The house has a super-tight building envelope built using porous concrete masonry blocks with eco-friendly mineral wool insulation. A high performing heat pump system provides the heating and cooling. However, natural ventilation is used to cool the house during the warm Sicilian summer month to minimize overall energy consumption. A PV system produces 160% of the energy the building needs annually. Domestic Hot water is provided by solar thermal panels. The building also utilizes a double flow heat exchanger to maximize energy efficiency. As a result, the building has an EUI of 25.4 KBtu/sf/yr.

Figure 64. Exterior image of the Project Botticelli in Italy (Google Images)

Israel – Eco360 Villa

The Eco360 Villa in Israel uses solar energy and passive design to create an energy positive building (Figure 65). The house is built using well insulated concrete thermal mas. The compact design employs geometrical optimization to generate a minimal volume, hence maximizing its overall efficiency. As a result, the largely heated by the energy generated by body heat and household equipment. Naturally ventilated facades provide ample cooling during the warm summer month. The ventilated high-performance facades create an air gap between the bamboo-like cladding and the concrete structure, amplifying convection and generating a micro ventilation effect leading to enhanced acoustic insulation, minimizing thermal bridging, increased energy savings, condensation prevention, and higher thermal insulation. A 16.2 KWp 45 solar panel photovoltaic array generates more than double of the electric consumption needs of the house.


Figure 65. Exterior image of the Eco360 Villa in Israel (Google Images)

Cyprus – PH Tseri

The PH Tseri house was the first Passivhaus Certified house constructed in Cyprus (Figure 66). The house was made from a sustainably harvested timber frame skeleton. The structure was super insulated with eco-friendly mineral wool insulation made from Knauf. The super insulated building envelope reduces the heating and cooling loads by 90%. A heat recovery ventilation system with a heat pump component was installed to provide for a comfortable and pleasant indoor environment throughout the year. The system provides 90% of the required fresh air with minimal energy loss. The house has high performing triple glazed windows with argon gas filling to minimize heat migration. The architect employed large windows to allow for ample natural daylighting and cross ventilation when opened. An efficient 2-panel solar hot water system saves over 25% of household energy loads. Deep overhangs on the west veranda helps reduce overheating from the afternoon summer sun. Lastly, all the bedroom windows have shutters to prevent overheating.

Figure 66. Exterior image of the PH Tseri house in Cyprus (Google Images)

Lebanon – Beit Misk Community

Considered to be a first of its kind in Lebanon, Beit Misk community offers its tenants a smart and eco-friendly approach to living (Figure 67). Dubbed the "Smart Village", the complex employs the best principles of smart urban design to provide a low energy approach to apartment living (Figure 68). The community achieved the Building Establishment Environmental Assessment Methodology (BREEAM) certification. Apartments are super insulated with ample thermal insulation utilizing a double concrete masonry block envelope system. Domestic hot water is provided via solar thermal systems. All units are equipped with efficient reduced emission gas heaters. Energy-saving LED lighting with daytime sensors eliminate and reduce the need for electric lighting, yielding a 50% reduction in energy use.

Figure 67. Exterior image of the Beit Misk Community in Lebanon (Google Images)

Figure 68. Aerial image of the Beit Misk Community in Lebanon (Google Images)

Best Practices Summary

Based on the analysis and research from various case studies and locations, the following lists encompass NZE best practice guidelines and strategies to be investigated and analyzed in the research. It's the aim of the research to formulate a systematic approach towards achieving NZE building practices within Lebanese multi-family apartment buildings.

General NZEB Best Practices:

- Super-insulated thermal envelope
- High performance HVAC and DHW systems
- High performance glazing systems
- Efficient lighting & appliances
- Renewable Energy

Climate-specific NZEB Best Practices:

- Ground-source/Air-source Heat pumps HVAC system
- Double cavity CMU envelope construction
- Double pane glazing
- Passive cooling via natural ventilation
- Passive heating via thermal mass
- Shading systems, both internal and external
- Solar thermal DHW systems

These strategies will form the basis of the modeling and simulation analysis to better assess the impacts of various parameters on energy consumption in a standard multifamily housing block in Lebanon. Accordingly, these typological and contextual strategies will provide the foundational elements for the upgraded building parameters.

Chapter 3: Research Design and Methods

Research Design

To address the research questions, hypothesis, and literature gaps, the following methodology was utilized: First, perception surveys were conducted, technical data evaluated, and regulatory barriers reviewed (Figure 69). Second, a quantitative iterative parametric energy modeling and simulation approach was employed to assess and analyze the data (Figure 70). Lastly, comprehensive optimal NZE guidelines and practices were recommended.

Figure 69. Research design methodology approach

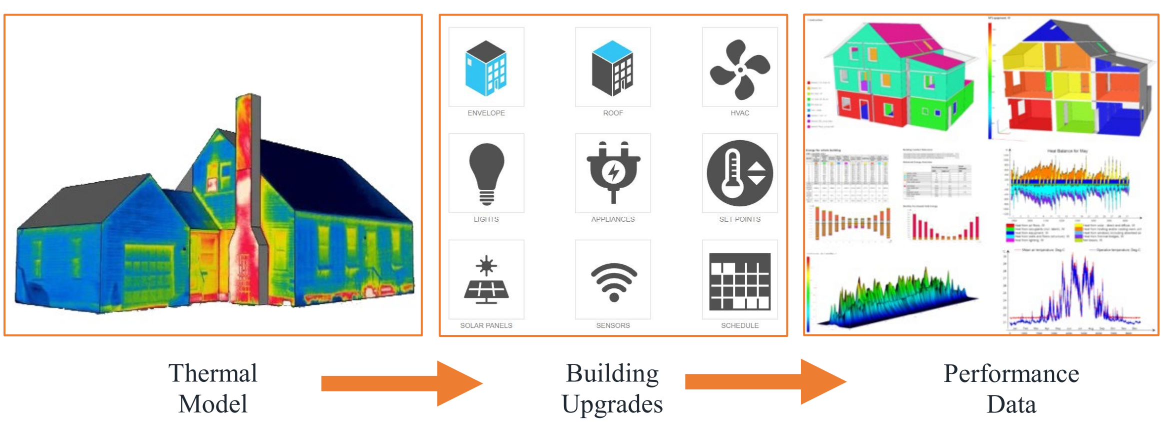

Figure 70. General overview of energy modeling and simulation workflow

The study used an integrated building components methodology to assess energy performance and evaluate the most optimal permutations of energy conservation measures to be utilized in a standard apartment building. The research design employed a "system dynamics modeling" approach, to simulate the impacts of interactions among various architectural variables (Figure 71) (NREL, 2016). This modeling analysis sought to investigate the impact of targeted variations of green building upgrades, encompassing optimal permutations of architectural building systems and design configurations, on energy consumption in a Lebanese apartment building. Energy use intensity (EUI) was used as the main energy performance indicator and primary response variable (Yılmaz, 2007). Major residential energy end-uses, such as heating, cooling, lighting, hot water, ventilation, and appliances, were measured and evaluated. To that end, various parametric energy modeling tools were utilized to evaluate and assess the information (DOE, 2016). Data needed for the modeling analysis were sourced from appropriate industry and building code databases. The analysis methodology employed optimized 3d computer simulations to gauge the impact of various architectural components on energy performance in an apartment building.

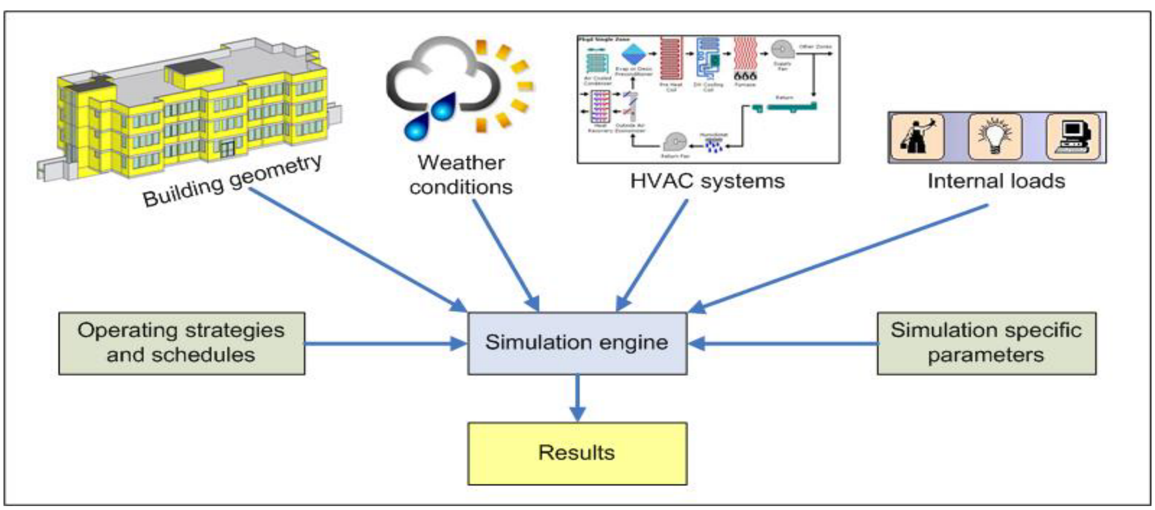

Figure 71. General overview of energy simulation engines data flow (DOE, 2016).

The research design for this analysis encompassed the following four overarching sequential steps, listed as follows, in the order in which they will be executed:

1. Established a baseline normalized energy and construction model with proper climate and location data. In order to normalize the data, a baseline benchmark model was set addressing the following components: building size/footprint, number of floors, apartment size, construction specifications (envelope, HVAC, Windows, insulation values, etc.), household number, number of bedrooms and bathrooms, energy use intensity (EUI), and annual total energy use. The EUI metric, a measure of annual energy consumed by a structure per unit of gross floor area, was utilized as the main performance index indicator (EIA, 2017). A minimum 5% improvement over baseline was used to establish the minimum allowable energy improvement threshold between standard apartment buildings and energy efficiency ones.

2. Simulated iterative parametric annual energy modeling runs assessing the impact of various architectural design variables. These included the following: building footprint/layout, building massing, roof characteristics, window to wall ratio, glazing placement and distribution, shading systems, etc. Thereafter, the top energy performance indicators (minimum 5% improvement over baseline) were identified as the top variables.

3. Simulated iterative parametric annual energy modeling runs assessing the impact of various building system variables. These included the following components: insulation levels, envelope construction, glazing specification, HVAC systems, DHW systems, lighting, setpoints, etc. Thereafter, the top energy performance indicators (minimum 5% improvement over baseline) were identified as the top variables.

4. Selected the most optimal variables from steps 2 & 3 (if applicable) and simulated iterative parametric energy modeling runs evaluating combinations of optimized architectural variables, to determine the most optimal energy performance indicators (minimum 50% improvement over baseline).

5. Lastly, added on-site energy generation to the most optimal parametric run and evaluated its impact on overall energy performance and Net Zero Energy feasibility.

Research Scope

The research focused on assessing and evaluating energy performance and consumption patterns in a standard Lebanese residential apartment building located in climate zone 1, where 70% of the population resides. The target market was middle to low-income housing apartment blocks, which constituted the majority of residential archetypes in the country. Typological data was collected via surveys, questionnaires, and literature review. The research employed an iterative parametric energy modeling and simulation analysis to assess energy performance and evaluate the most optimal permutations of energy conservation measures in the context of a Net Zero Energy framework.

All baseline energy simulation assumptions were based on building code guidelines and construction specification in practice today. The modeling and simulation protocols were consistent with industry references and practices. Baseline code-reference standard apartment building components were used to initiate the modeling process (Table 3, 4 & 5). Basic standard architectural and energy systems specifications as well as Thermal Transmittance Values assumed for the baseline case are outlined below, as adopted from industry standards, construction norms, and literature review (Appendix E).

Table 3. Standard architectural and energy systems specifications assumed for the baseline case

Category	Baseline Specifications
Archetype	Standard residential square-shaped apartment block
Location	Climate Zone 1 – Coastal/Inland
Built Year	New construction
Building Size/Area	1600 square meters
Number of Floors	4
Total Number of Apartments	8
Number of Apartments Per Floor	2
Apartment Size/Area	175 square meters
Number of Bedrooms Per Unit	3-4
Number of Bathrooms Per Unit	3
Household Occupancy	4
Cooling System	Plugin provisional air conditioning window units
Heating System	Plugin electric heaters OR Diesel furnace/boiler via hot water pipes (Chauffage)
Hot Water System	Tank electric
Construction Typology	Heavy weight concrete/CMU construction
Wall Systems	Single 15cm CMU construction system with no insulation
Floor & Roof Typology	Flat concrete slab (4" floor, 6" roof)
Glazing Systems	Low-performance single pane windows, 15% WWR
Reference Thermal Energy	Surveyed Existing EUI = 141.5* kWh/m^2/yr Measured/Calculated Existing EUI = 184* kWh/m^2/yr **Surveyed EUI Range: 135-148 kWh/m^2/yr* **Measured EUI Range: 148-220 kWh/m^2/yr*

Table 4. Energy demand (KWh/m^2/yr) of residential building end uses (LCEC, 2018)

Climate Zone 1	Residential Standard	Residential Seasonal
Heating	3	6
Cooling	78	64
Ventilation	7	7
Lighting	13	3
DHW	10	2
Dehumidification/Humidification	36 / 1	32
Total	148 KWh/m^2/yr	116 KWh/m^2/yr

Table 5. Reference Thermal Transmittance values (W/m^{2}K) (Lebanese standard, 2010)

Climate Zone	Building Category	U-Value Roof	U-Value Wall	U-Value Windows	U-Value Grd Floor
Zone 1 - Coastal	Residential	0.71	1.60	5.80	1.70
Zone 2 – Mid Mountain	Residential	0.63	0.77	4.00	0.77
Zone 3 – Inland Plateau	Residential	0.63	0.77	4.00	0.77
Zone 4 – High Mountain	Residential	0.55	0.57	3.30	0.66

The research assessed and analyzed various architectural metrics utilizing a multi-criteria variable approach. The following architectural indicators served as the main independent variables within the experimental study: envelope construction typology, insulation levels (walls, roof, ceiling, foundation), heating system, cooling system, domestic hot water system, glazing, lighting, building geometry, building footprint, building massing, roof characteristics, and window to wall ratio. The primary dependent response variable was the energy use intensity performance index (EUIp).

The following databases and agencies were sourced for various data pertaining to research methods and design: Thermal Standard for Buildings In Lebanon, Lebanese Construction Law, Energy Information Administration (EIA), U.S. Census, International Energy Conservation Code (IECC), Department of Energy (DOE)–residential building prototype models, Existing Industry Standards and Guidelines, International Green Construction Code, National Association of Home Builders Guidelines (NAHB), National Renewable Energy Laboratory (NREL), U.S. Green Building Council (USGBC), New Buildings Institute (nbi), and the International Living Future Institute (ILFI).

Energy Modeling Tools, Workflow, and Framework

The research employed a quantitative iterative parametric energy modeling and simulation approach to assess and evaluate the impacts of various architectural variables on energy consumption in a standard Lebanese apartment building. The Cove.tool was employed as the primary parametric energy modeling platform to evaluate the relationship between various architectural indicators and energy performance. DesignBuilder and Sefaira were also used as secondary tools to normalize the data. DesignBuilder is a fully integrated modeling and simulation platform used to assess the environmental performance of buildings. It employs the Department of Energy's EnergyPlus™ tool as the main simulation engine, considered the industry standard for dynamic building energy simulation. Sefaira, a cloud-based simulation platform for high-performance design, that employs EnergyPlus™ as the driving simulation engine. The Cove Tool, an automated design platform for intelligent building performance and parametric optimization, was utilized as the primary energy simulation platform. EnergyPlus ™ engine is a whole-building energy simulation platform designed to simulate buildings energy consumption for cooling, heating, lighting, and ventilation (DOE, 2016). It's considered one of the industry's more robust tools offering the following capabilities: integrated parametric analysis, thermal zones, heat balance calculations, sub-hourly-hourly-monthly-annual runs, heat transfer, illuminance calculations, component-based HVAC, solar energy analysis, and energy end-use breakdown. The impact of energy-efficient building upgrades was evaluated using Cove's (Figure 72), DesignBuilder's (Figure 73), and Sefaira's (Figure 74) EnergyPlus simulation engine in a sequential analytical parametric approach. Numerous diverse iterations of simulations were modeled to analyze the interactions systematically and dynamically between different permutations of variables and their impact on energy performance (Granadeiro et al, 2013). The research adopted a multi-criteria sequential energy modeling and simulation approach (Figure 75), following a gradual methodology starting with establishing a baseline code-referenced model with proper climate and location data; second, modeling various parametric simulation runs assessing respectively separate iterations of building design configurations and building system upgrades; third, isolating the most optimal energy-performing indicators from each category; and fourth, modeling and testing the most optimal permutations of indicators in an effort to generate the top energy indicators.

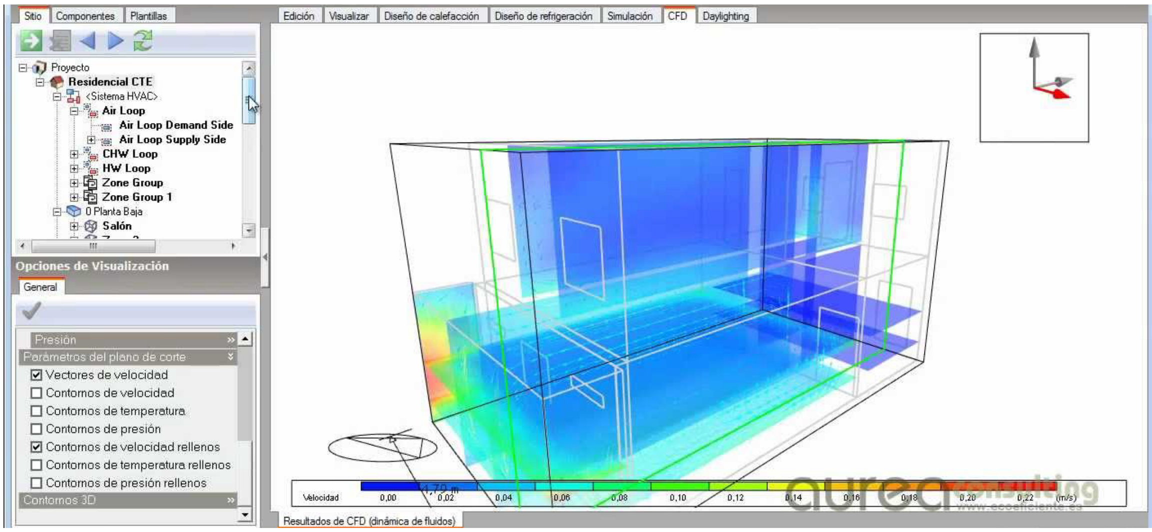

Figure 72. DesignBuilder interface (DesignBuilder, 2020)

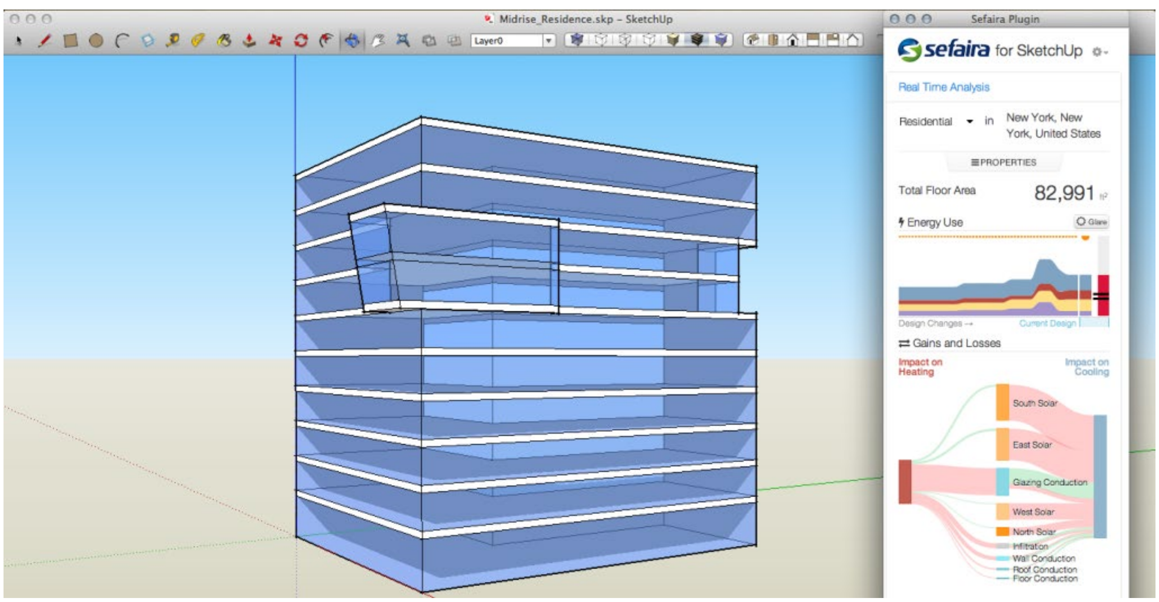

Figure 73. Sefaira plugin within Sketchup interface (Sketchup, 2020)

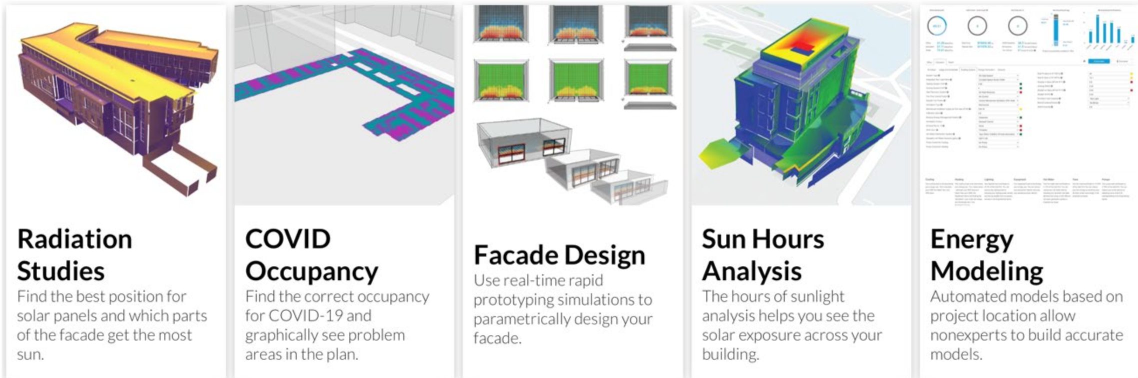

Figure 74. Cove tool optimization interface (Cove, 2020)

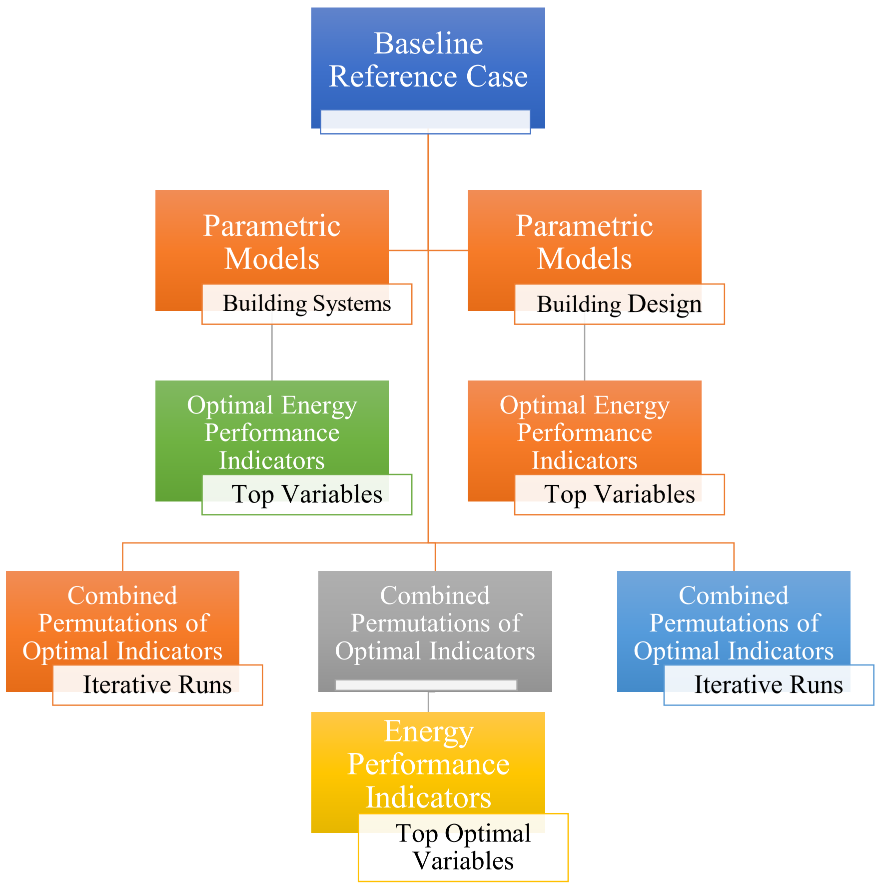

Figure 75. Chart summarizing the framework of the project's modeling environment.

The research design methodology and framework were guided by the principal premise of achieving Net Zero Energy design via the most optimal set of architectural variables and green building upgrades. To that end, the following sequential framework (Figure 76) was adopted to guide the modeling and simulation process: first, iteratively tested various diverse building design configurations and variations to identify the most optimal high performing indicators; second, iteratively tested various diverse building system upgrades to identify the most optimal high performing indicators; next, iteratively modeled and simulated diverse combinations of the most optimal architectural variables to achieve a minimum of 50% reduction in energy consumption below the modeled energy use intensity baseline; Lastly, applied onsite renewable energy to achieve a Net Zero Energy status. An incremental Net Zero Energy approach was adopted encompassing two modeling phases. The first phase explored energy optimization via design parameters, passive strategies, and active systems, leading to a Net Zero Energy-ready building. Thereafter, on-site renewables were added to further optimize the model and generate a Net Zero Energy-ready Building. The cove tool was used to generate and evaluate various energy to cost bundles and scenarios, including, baseline bundle, top optimized bundle, and lowest cost bundle.

Figure 76. Illustration showing the sequential Zero Energy approach

Chapter 4: US & Lebanese Energy Efficiency Perceptions

Introduction

Bridging the perception gap of energy consumption and efficiency is a critical driver in the proliferation of energy conservation measures and climate change mitigation. Energy efficiency perceptions are an integral component of the ongoing efforts to advance zero energy housing as a socially, economically, and environmental viable alternative to traditional housing. To that end, the research employed the use of online surveys as a data collection tool to gauge overall perceptions of Zero Energy Housing (ZEH) and Energy Efficiency (EE) in the US and Lebanon, as well as identify knowledge gaps. National US polling have shown that most people consider curtailment as the most effective strategy to reduce energy consumption in lieu of implementing energy efficiency improvements and conservation measures, in contrast to experts` recommendations. This so-called public perception gap reinforces the need to ramp up educational and awareness efforts to further improve the public's knowledge of energy consumption and saving patterns. These efforts could pay dividends in the long run. US energy efficiency perceptions are often influenced by misconceptions and misinformation propagated by various entities for various reasons. The end result is a general skepticism of the efficacy of such efforts leading to hesitance towards adopting energy conservation measures. Aa a result, PEW Research Center polling shows only 60% of US participants are concerned about climate change. On the other hand, the Lebanese population is well aware of the perils of climate change and excessive energy use. Nonetheless, Lebanon has not adopted the necessary measures to curtail climate change and associated air pollution. The country also has the highest energy use per capita compared to its regional counterparts. As a result, Lebanon experiences frequent power outages, blackouts, and energy shortages. Furthermore, access to reliable and consistent electrical supply remains intermittent at best. To that end, when asked if they would upgrade their home into an energy efficient residence such as ZEH, over 80% of participants answered yes. Moreover, 90% of Lebanese expressed concern about climate change and rising energy prices. The research employed online surveys to gather data about ZEH perceptions and attitudes. Data collected via the online surveys included questions about knowledge of ZEH, interest in ZEH, perceptions of ZEH, and barriers to ZEH. It also included few general questions about energy use and climate change. The surveys collected data from a sample cohort including homeowners (anyone not a student or building professional), college students, and building professionals (architects, contractors, builders, developers, researchers, etc). The survey initiative is intended to educate and promote the concepts of Zero Energy Housing to the public, in an effort to accelerate the adoption of energy conservation and efficiency measures. A comparative analysis of survey results from both locations will be presented to fully understand overall energy efficiency perceptions and attitudes. Survey results will be instrumental in providing a foundational knowledge base for energy efficiency and Zero Energy Housing perceptions. The results will be used to shape and direct the narrative to address energy efficiency perception gaps in Lebanon to advance the concepts of Zero Energy Housing.

Surveying Methodology: Design, Distribution & Analysis

Surveys constitute a systematic approach of collecting data from a sample cohort for the purpose of defining characteristics of the population at large. The design of the research survey encompassed four sequential steps, (1) Defining the survey constructs and target population, (2) Identifying the sampling type and data collection mode, (3) Designing the survey questions, (4) Collecting the data.

Defining the Survey Constructs and Target Population

This initial phase defined the scope of the survey. The main objective of the survey was to capture and define people's perceptions and knowledge regarding the Zero Energy Housing (ZEH). The survey constructs gauged people's perception of ZEH, energy efficiency, policies and barriers to energy conservations, and attitudes towards the built environment. The survey included questions about knowledge of ZEH, interest in ZEH, perceptions of ZEH, and barriers to ZEH. It also included questions about the performance of participant's own home or place of residence. Collected data was used to provide background information for the research as well as gauge the audience's knowledge and familiarity with ZEH. The data was utilized to identify gaps and provide solutions accordingly.

The target population of the survey were homeowners, renters, prospective homeowners, anyone planning for a future residence, college students, and building professionals. Building professionals include architects, engineers, designers, contractors, researchers, developers, etc. The survey was administered and distributed electronically to target populations in the United States and Lebanon for comparison. The two locations were used to gauge response variances between the two surveyed populations.

Identifying the Sampling Type and Data Collection Mode

The research survey employed a non-probability sampling approach to collect and gather data. Sample selection was based on a subjective judgement rather the randomized selections. In this type of sampling methodology, the results allow for inferences about general opinions, experiences, and perceptions of the overall population. Non-probability sampling is less robust statistically than probability sampling, but it's less cumbersome to administer from a budgetary and time standpoint. The main objective of the research survey was to gain insight and understanding about individual experiences relating to Zero Energy Housing. Hence, it is presumed that generalization (probability sampling) is not necessary. To that end, the surveys utilized a purposive sampling technique, where answers were obtained from a selected and targeted group of respondents. This specific technique was chosen for the identification and selection of data-rich cases and to produce samples that can be reasonably anticipated to be typical of the population. To that end, data collection mode utilized electronic surveys. A specified sample size was not needed since the survey is utilizing a non-probability sampling methodology. The survey was administered via emails and various social media platforms including LinkedIn, Facebook, Instagram, WhatsApp, etc.

Designing the Survey Questions

The research survey questions and information sheet are outlined in Appendix C and D. The survey questions were designed and developed in accordance with the survey constructs and overall scope. It's the researcher's objective to minimize survey errors and maximize validity. Nonetheless, survey errors are unavoidable. To that end, survey questions were designed to maximize the validity and robustness of the survey using the following guidelines:

- Survey was divided into defined and clear sections with a sequential progression.
- Concise and clear language used in all questions.
- Appropriate and consistent format was adopted for all questions.

- Most questions had clear criteria and options.
- Questions were designed to include one question at a time.
- Most questions utilized a Likert scale, where possible.
- Questions were relevant to respondents.
- Complete sentences were used in a question form.
- Complex terminologies were simplified or explained and defined, such as Zero Energy Housing.
- Survey respondents were given the choice to opt out of the survey.

Most of the common errors associated research surveys do not apply to this survey since it utilizes a non-probability sampling approach. Hence, processing errors were the primary concern as it relates to the accurate coding of the response data. To that end, certain tools such as Microsoft Excel were utilized to streamline the data entry process and establish a clear coding system.

Collecting the data

The research surveys were designed, developed, and administered through Google Forms and Qualtrics. The US survey was constructed via a Google Forms template, while the Lebanese survey utilized Qualtrics, due to the ease of incorporating multiple languages to accommodate the Lebanese population (Arabic and French). Data was collected via summary reports and individual responses. Excel spreadsheets were generated for each survey that includes all questions and answers categorized and classified by typology cohort. Processing errors were handled through a well-defined clear coding system.

Analysis of Survey Data and Results

The survey data was collected, collated, and organized in an excel database system. A spreadsheet hierarchical structure was employed to segregate and classify the data into various categories and classifications. Tools such as Microsoft Excel, SPSS, and Minitab were used to analyze the survey data and generate the graphical results. To that end, the survey data analysis followed 4 main sequential steps:

1. Exploratory Data Analysis – this step encompassed survey data evaluation as an initial process to assess the scope of collected information.
2. Discerning Main Findings – this step initiated raw data processing, cleaning, and entry into a database. Summary finding reports were generated and produced.
3. Data Archiving – this step involved data instrumentation recording and storage.
4. Data Synthesis – this step utilized Excel as the primary data analysis tool to generate the various results and data point comparisons.

Background on Existing US & Lebanese Energy Patterns

US Energy Consumption Patterns

The built environment has a substantial impact on energy consumption. Buildings are a major contributor to greenhouse gas emissions. In the United States, the residential building sector consumes more than half of the total primary energy attributed to the building sector (EIA, 2017). Moreover, 80% of the total U.S. residential energy is consumed by single-family residential structures (RECS, 2009). Detached single-family homes are the largest energy users among all residential structures in the US (EIA, 2017). The size of US homes continues to increase relative to homes built in earlier decades, a noteworthy trend as most energy end-uses (heating, cooling, lighting, hot water, etc.) are affected by building size and footprint. In 2009, the EIA estimated 48% of residential energy consumption was attributed to cooling and heating end uses in an average U.S. residence (RECS, 2009). Nonetheless, EIA data show an increasing number of energy efficiency trends, specifically among cooling, heating, and refrigeration equipment in the U.S. (EIA, 2017), leading to significant reductions in energy consumption compared to two decades ago. However, these energy savings have been offset by the proliferation of energy-consuming devices in our homes over the past few years. The agglomeration of the products such as televisions, dishwashers, clothes washers, DVDs, DVRs, cell phones, audio-video equipment, and mobile devices, have significantly impacted the energy outlook of U.S. homes. As a result, U.S. residential sector contribution to greenhouse gases emissions is steadily increasing. To circumvent that alarming trend, various efforts have been undertaken to address this problem via residential code improvements, industry initiatives, and technology advances. EIA's 2020 short term energy outlook indicates a stable consumption of energy in residential buildings. It is also forecasting a slow increase in energy consumption between 2020 and 2050, compared to other end-use sectors (EIA).

Lebanese Energy Consumption Patterns

Lebanon is an energy intensive country, surpassing consumption patterns in many neighboring southern Mediterranean nations and Europe. Its electricity sector has also been plagued by corruption, inefficiencies, and monopolies. Moreover, energy consumption patterns have been steadily increasing and are projected to continue in the next decade (World Energy Council, 2016). Energy consumption patterns are heavily influenced and driven by market forces and major geo-political events. To that end, Lebanon imports liquid petroleum gas and oil to meet more than 90% of its primary energy needs (Azar, 2010). This dependency on oil imports have destabilized the country's already unreliable energy market. As a result, the energy and electricity sector have failed to meet the demands of domestic energy needs, causing severe shortages in supply and inability to meet primary consumption needs. Lebanon experiences protracted power outages that have led inevitably to the rise of unorganized and unregulated private generation sector to compensate for the gap in energy production (Yathreb, 2016). Hence, Lebanese households are burdened with two electrical bills. Lebanese citizens pay the highest electric bills in the region, while experiencing the lowest quality service. Beyond the financial strains imposed by the unreliable energy market, social and health concerns have also risen. Equitable access to a reliable electrical power supply has been plagued by selective distribution based on socio-economic status and location. Decades of un-regulated energy market and a heavy dependence on fossil-fuel imports have also exacerbated air pollution problems in Lebanon. The building sector in Lebanon is one of the major drivers of energy consumption and associated air pollution. The residential sector consumes around 40% of the total generated electricity, the largest amount in the country. Nonetheless, robust energy conservation measures are absent in residential construction and code development. Consequently, energy efficiency measures and upgrades aren't widely adopted due to the lack of proper legislative system with adequate monitoring agencies for enforcing and monitoring green construction practices (Missaoui, 2012). As a result, the adoption and implementation of the much-needed residential sustainable construction techniques and green building upgrades have been very slow and, in some instances, non-existent. Nonetheless, interest in energy performance has increased in the last few years, albeit within the commercial building sector. This further reinforces the need to promote, educate, and incentivize the adoption and implantation of robust residential energy conservation measures.

Preliminary and Exploratory Survey Results

General Respondents Classification and Distribution

The initial exploratory analysis of survey results encompassed 1110 respondents from the United States of America (US) and Lebanon (LB), the two primary locations of the research study (Figure 77). 565 respondents were from Lebanon, distributed across its major regions, and 545 respondents from the USA, heavily concentrated in the Northeast region (Figure 78). It's important to note that Lebanon's cohort represented a higher percentage of its population than did the US cohort.

Figure 77. World map depicting the two primary locations targeted for the research survey, USA & LB

Figure 78. Percentage of respondent's distribution from each location, US & LB

The primary survey respondents were homeowners (current, future, etc.), college students (diverse majors of study), and building professionals (engineers, builders, architects, contractors, researchers, etc.) (Figure 79). Homeowners constituted the largest percentage of respondents in both locations at 52%, followed by students (26%) and building professionals (22%) (Figure 80). Homeowners constituted 49% of total US respondents, followed by students at 33% and building professionals at 18% (Figure 81). Lebanese homeowners represented 55% of total respondents, followed by building professionals at 26% and students at 20% (Figure 82).

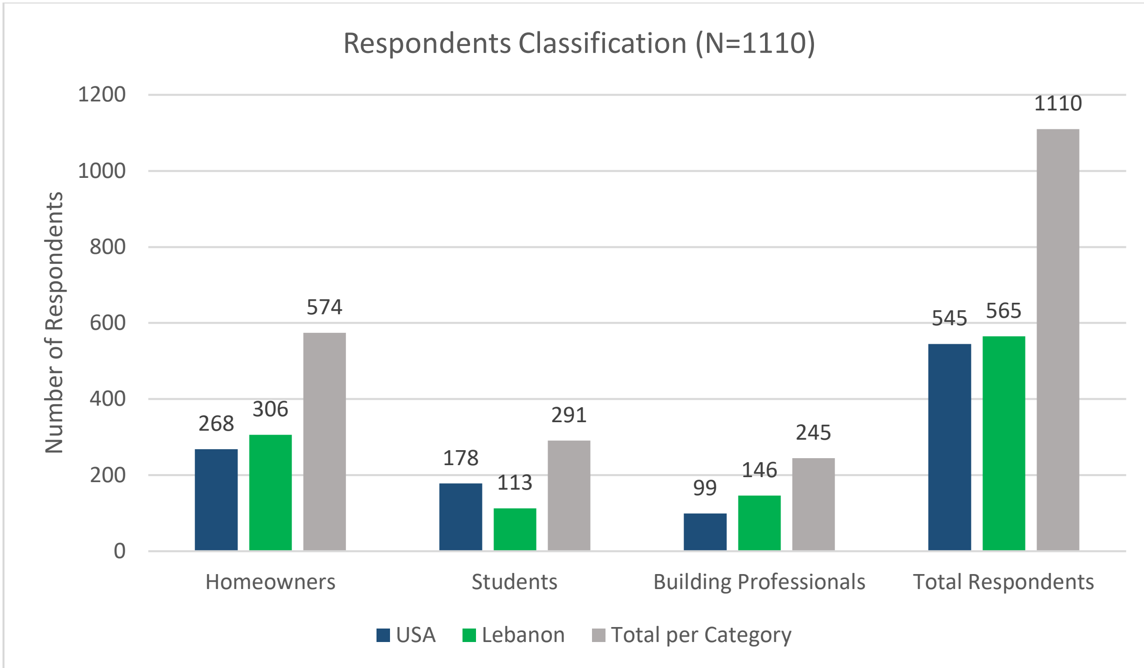

Figure 79. Distribution of respondents across the US and Lebanon.

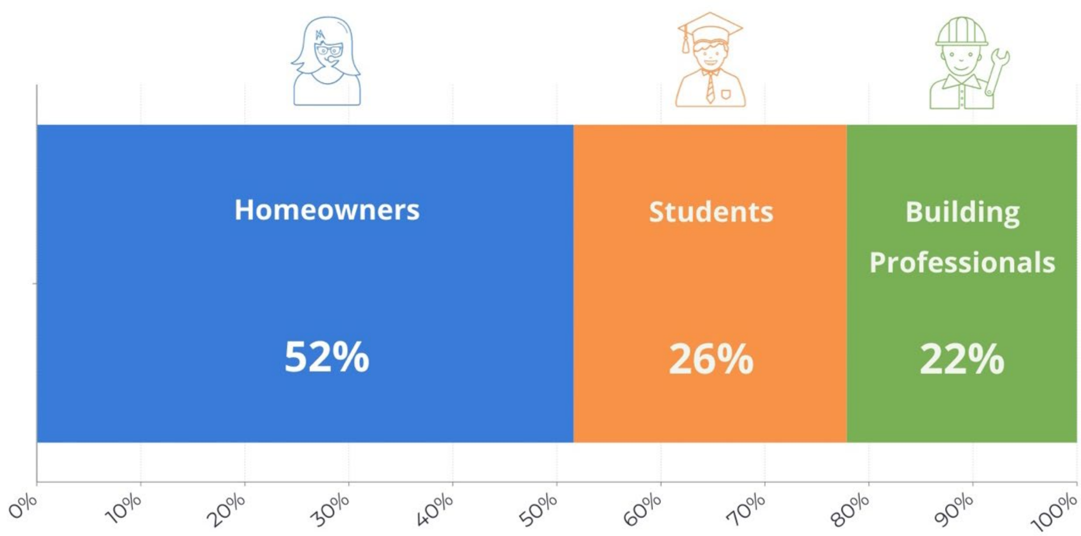

Figure 80. Total percentage of US & LB respondent distribution by classification

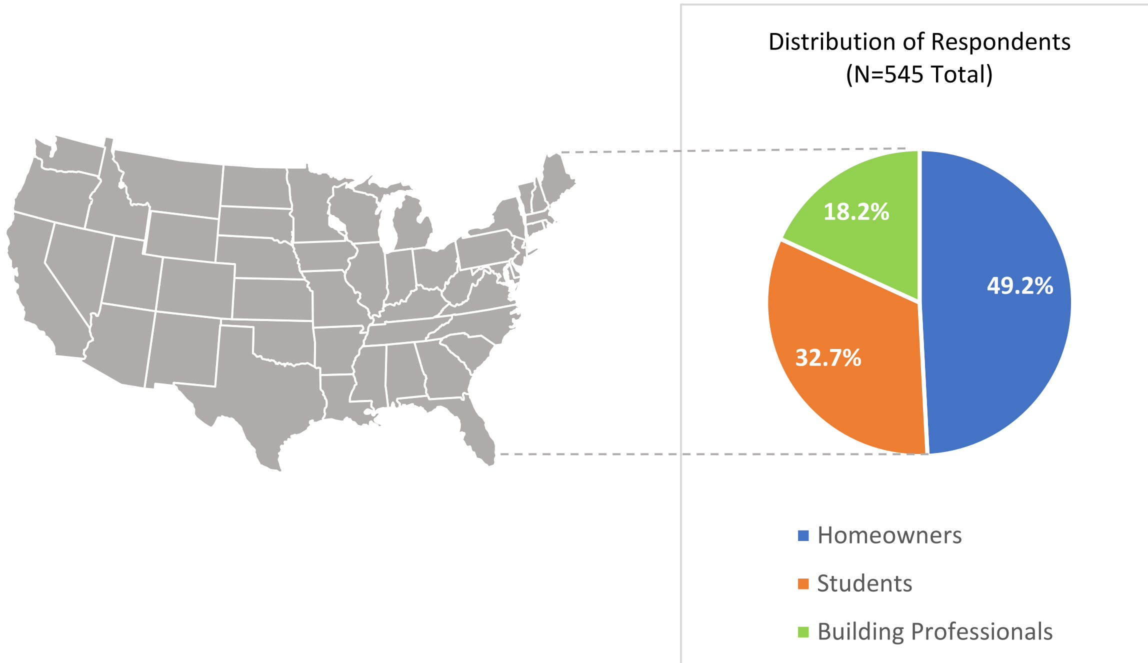

Figure 81. Total percentage of US respondent distribution by classification

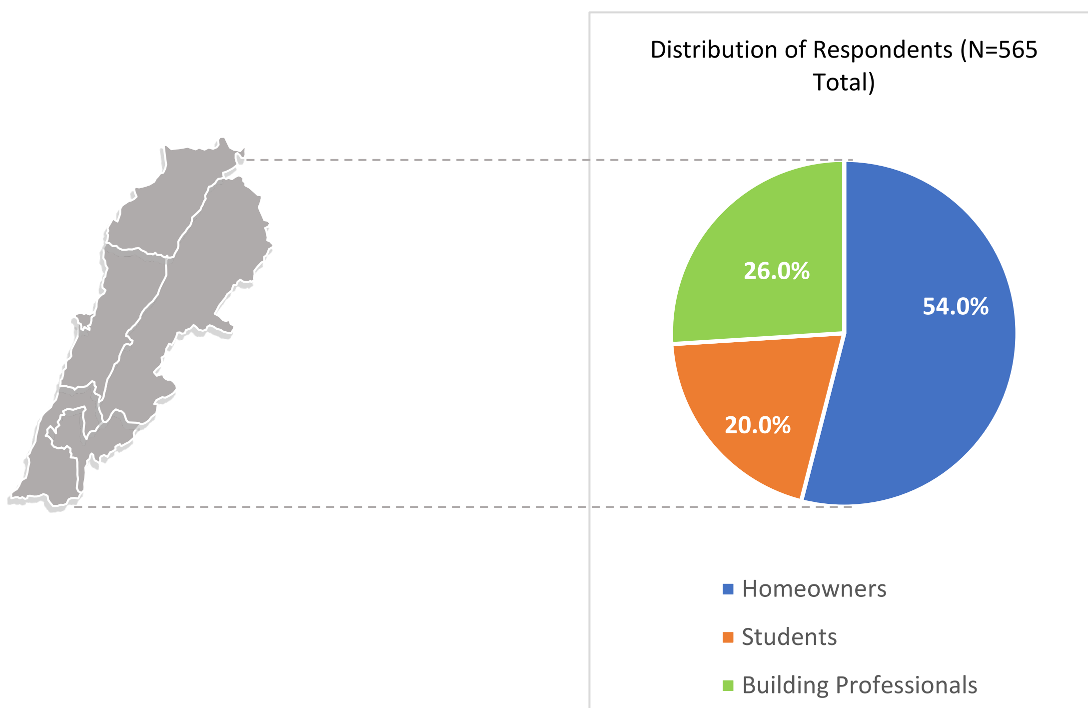

Figure 82. Total percentage of LB respondent distribution by classification

When analyzing the specific make-up targeted populations amongst building professionals and students, respondents with architecture-engineering-construction (AEC) backgrounds constituted a significant part of the sample cohorts. To that end, architects comprised 43.5% of total building professionals. The remaining 56.5% were distributed across a wide spectrum of professionals including contractors, engineers, researchers, developers, academics, etc. Architects represented 50% and 37% of total US and Lebanese building professional respondents respectively (Figure 83). Similarly, students from the architecture, engineering, and construction disciplines also dominated the sample cohorts, representing 54% of total student respondents in both countries. 60% of US student respondents were from AEC programs, compared to 44% of Lebanese student respondents (Figure 84).

Figure 83. Architect Respondent distribution among Building Professionals in the US & LB

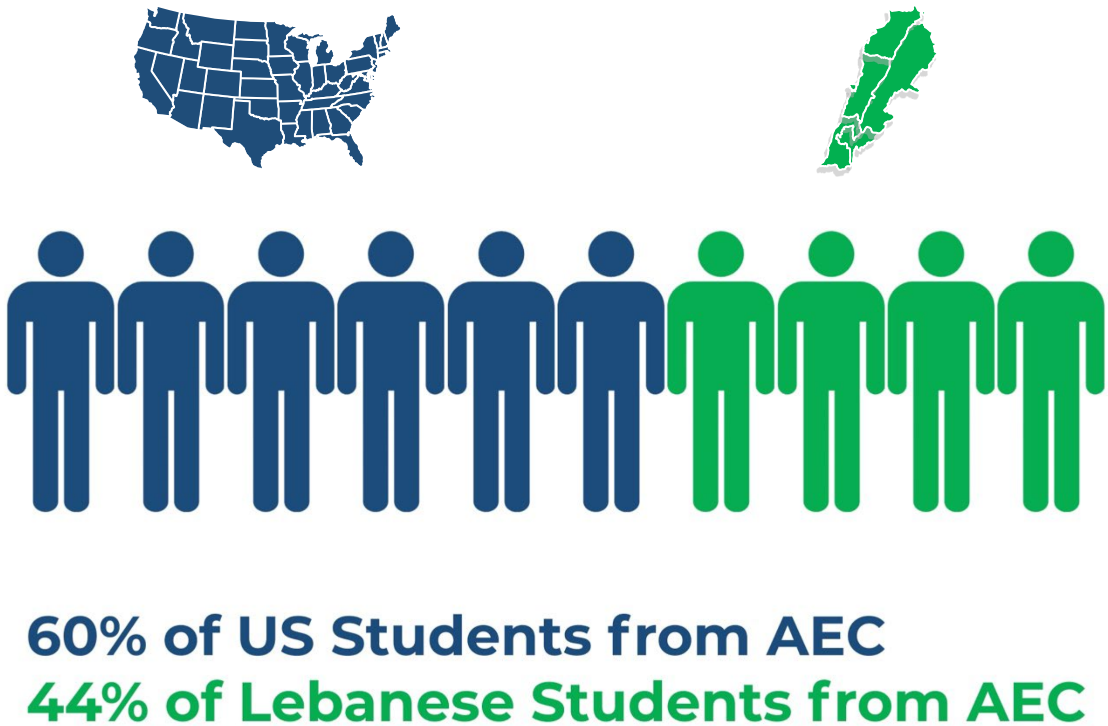

Figure 84. AEC Respondent distribution among Students in the US & LB

Significant efforts were undertaken to ensure respondents are representative of most climate zones/regions in both locations. The geographical distribution of US respondents' location is highlighted in Figure 85 (USA). In the US, 80% of survey respondents were from the Northeast region. Nonetheless, US survey respondents encompassed all US climate zones. 12% of survey respondents came from the South, 5% from the West, and 3% from the Midwest. Nonetheless, most of the survey participants were from the Northeast region, and specifically the State of Pennsylvania (PA). 78% of homeowner respondents, 91% of student respondents, and 69% of building professional respondents were from the Northeast. Furthermore, 70% of homeowner respondents, 82% of student respondents, and 58% of building professional respondents came from Pennsylvania (Figure 86).

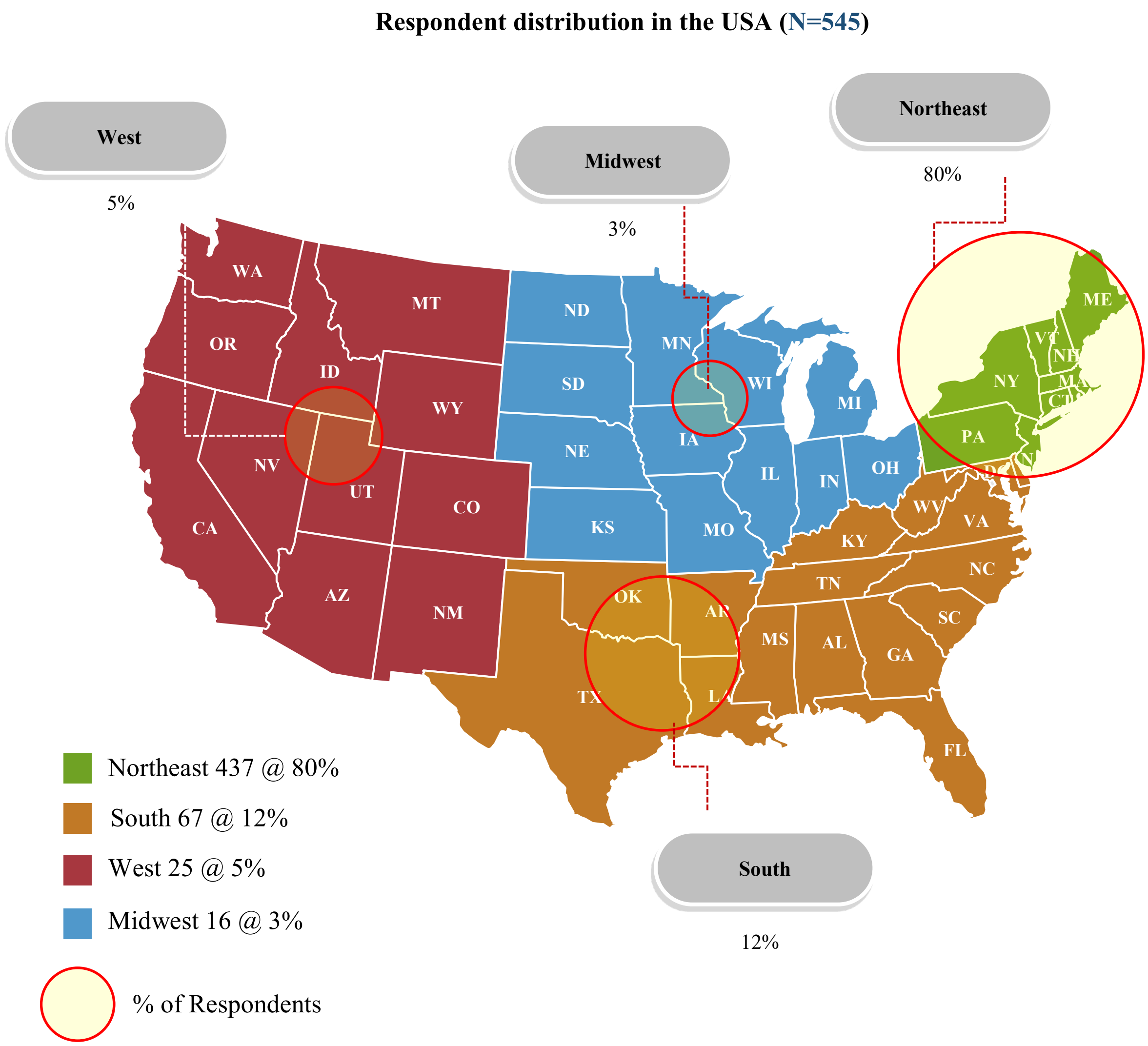

Figure 85. Map showing the geographical distribution of US respondents

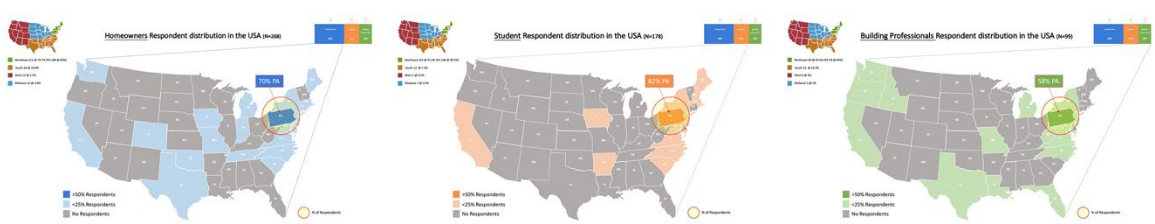

Figure 86. Maps showing the geographical distribution of homeowner/student/building professional respondents in the US

Similarly, Lebanon's survey respondents were representative of the country's diverse climate zones and regions (Figure 87). 40% were from the North Lebanon region; 27% from Mount Lebanon; 20% from the capital Beirut; 6% from the South, and 5% from the Beqaa region. 45% of homeowner respondents, 46% of student respondents, and 38% of building professional respondents were from the North Governate region (Figure 88).

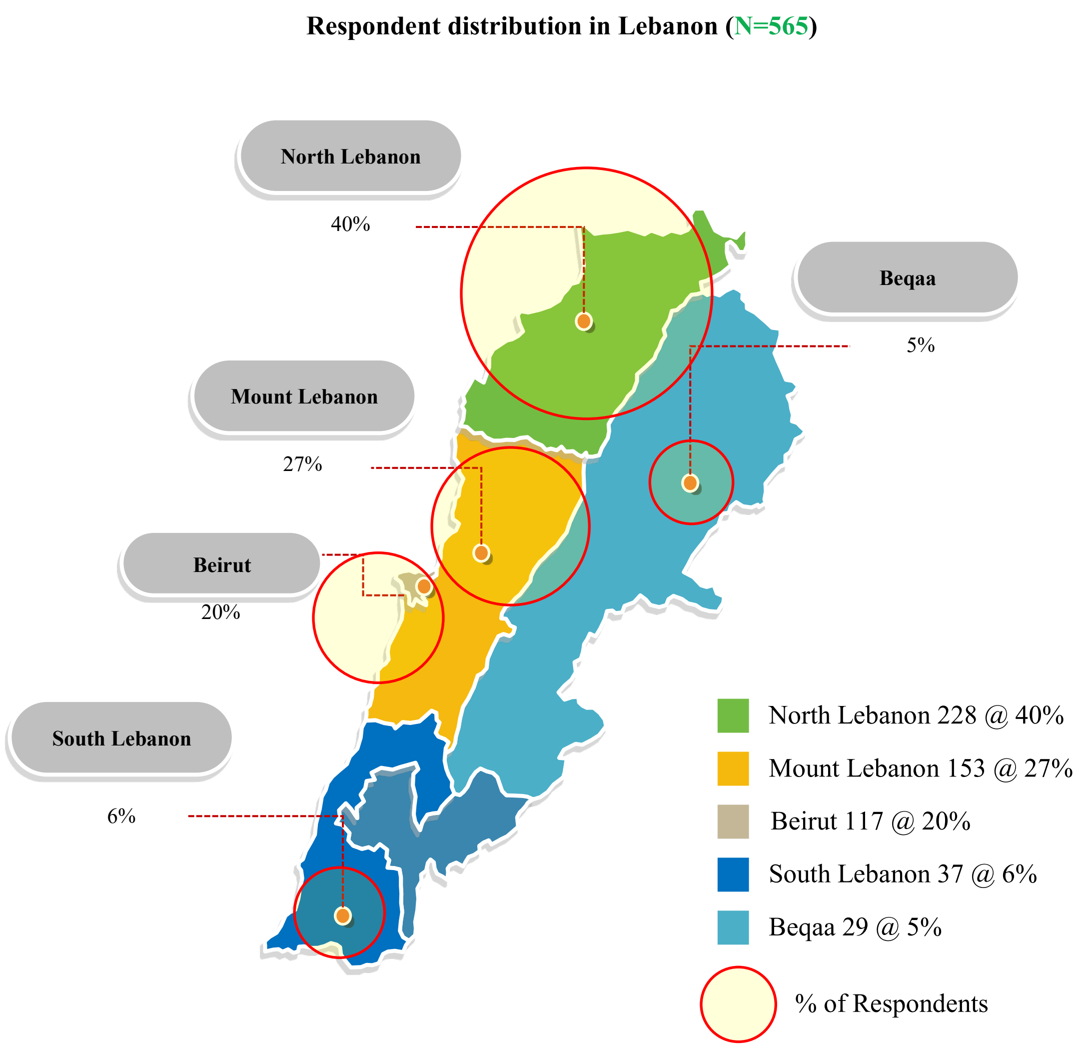

Figure 87. Map showing the geographical distribution of Lebanese respondents

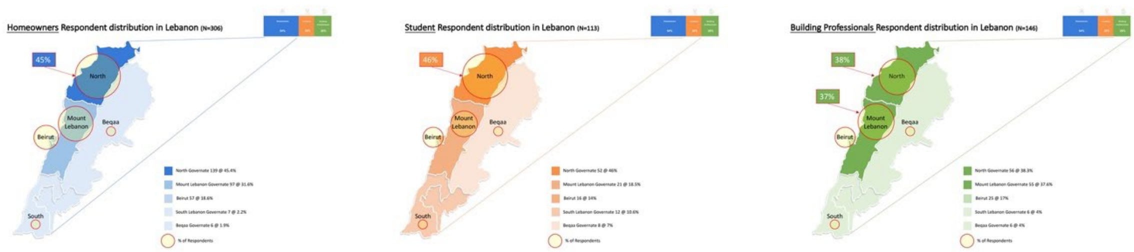

Figure 88. Maps showing the geographical distribution of homeowner/student/building professional respondents in Lebanon

Surveys (Appendix C and D) were distributed electronically to various stakeholders utilizing direct email communications to potential respondents encompassing homeowners, college students, and building professionals. Furthermore, the survey was also posted on various social media various platforms such as Facebook, Instagram, WhatsApp, and LinkedIn (Figure 89). To that end, IRB approvals were obtained from higher education institutions in the USA (Carnegie Mellon University-CMU) and Lebanon (Lebanese American University-LAU).

Figure 89. Social media platforms utilized for survey distribution

Preliminary and Explanatory Analysis of Responses

The initial exploratory analysis of survey results encompassed several survey questions and topics ranging from knowledge and perception of Zero Energy Homes to barriers towards implementing Zero Energy Housing (Figure 90). The analysis evaluated responses from both the US and Lebanon, encompassing homeowner, student, and building professional respondents.

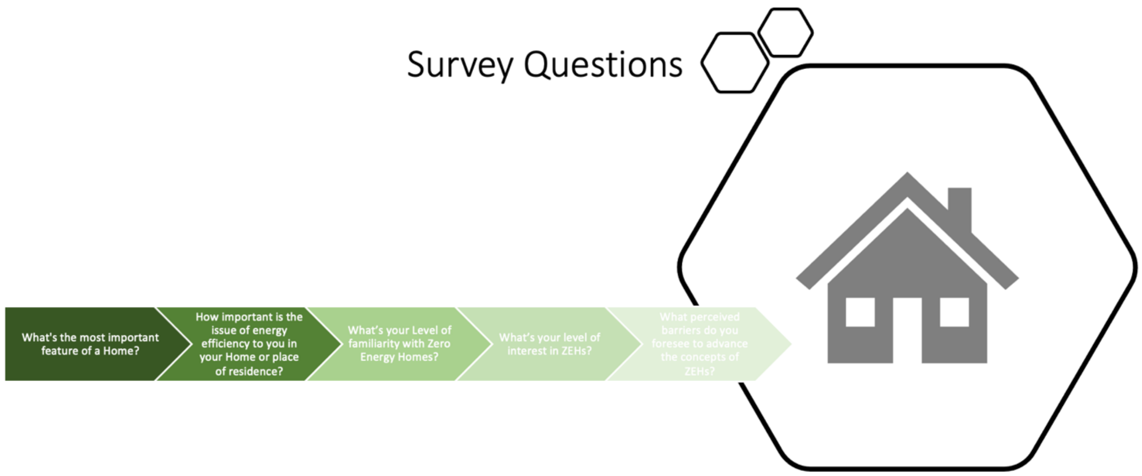

Figure 90. Five primary questions analyzed in the survey

Topic # 1: The Most Important Feature of a Home

The first analyzed question asked respondents to rank the most important feature of a home in their opinion, encompassing performance, aesthetics, affordability, and durability. The majority of respondents in both locations ranked durability as the most important feature of a home, followed by performance, affordability, and aesthetics (Figure 91).

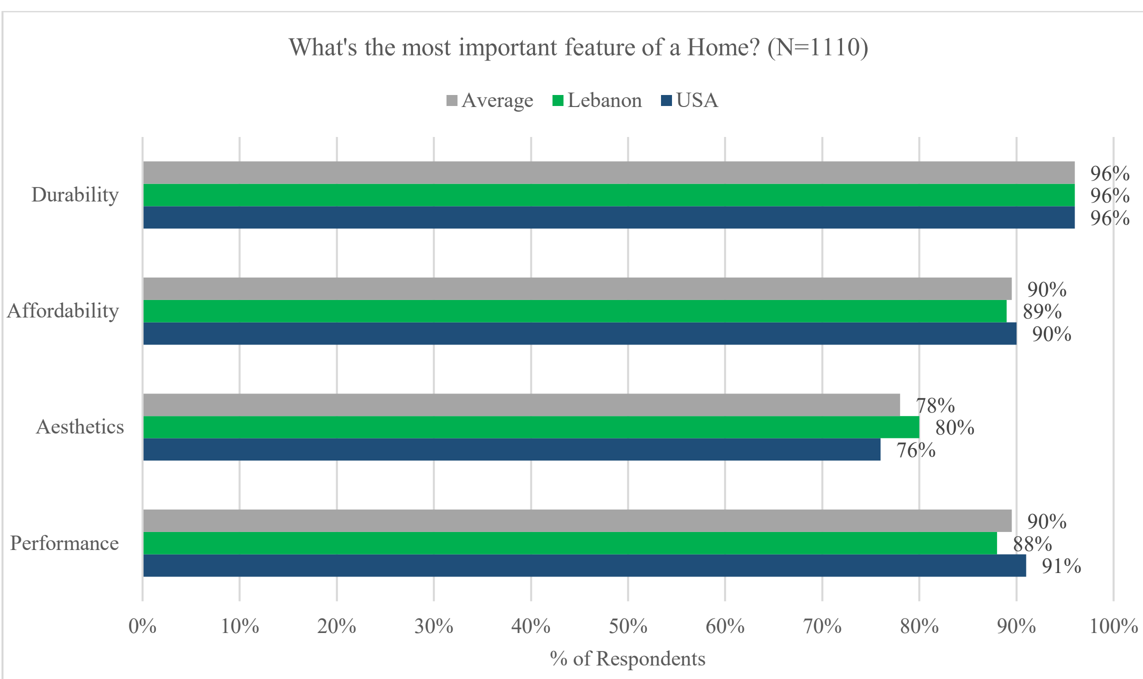

Figure 91. What's the most important feature of a home?

Durability was the option most selected, when comparing certain States representing various US climate regions, as the most important feature of a home (Figure 92). On the other hand, Lebanese respondents in various climates zones selected both durability and performance as the two most important features of a home (Figure 93).

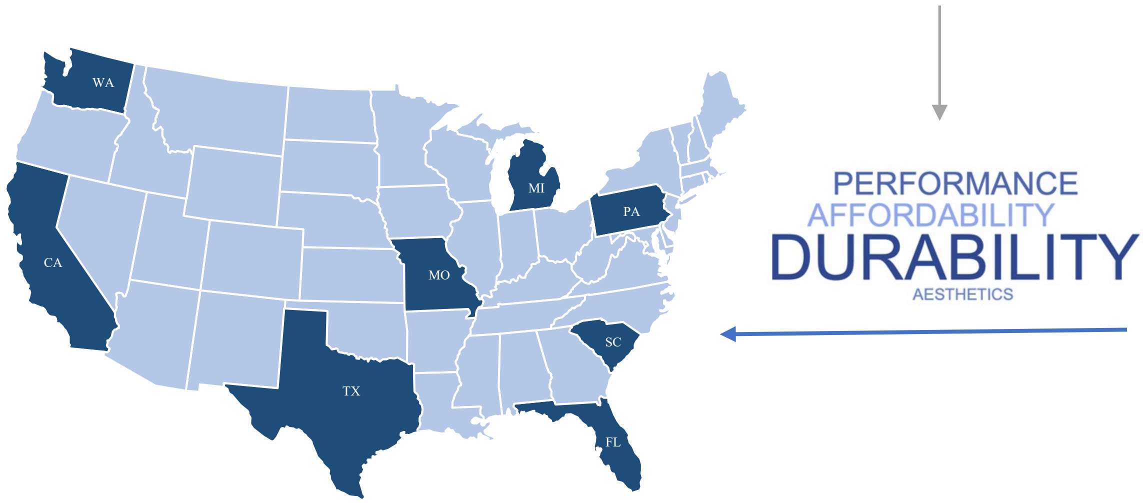

Figure 92. What's the most important feature in a home (Certain US States)?

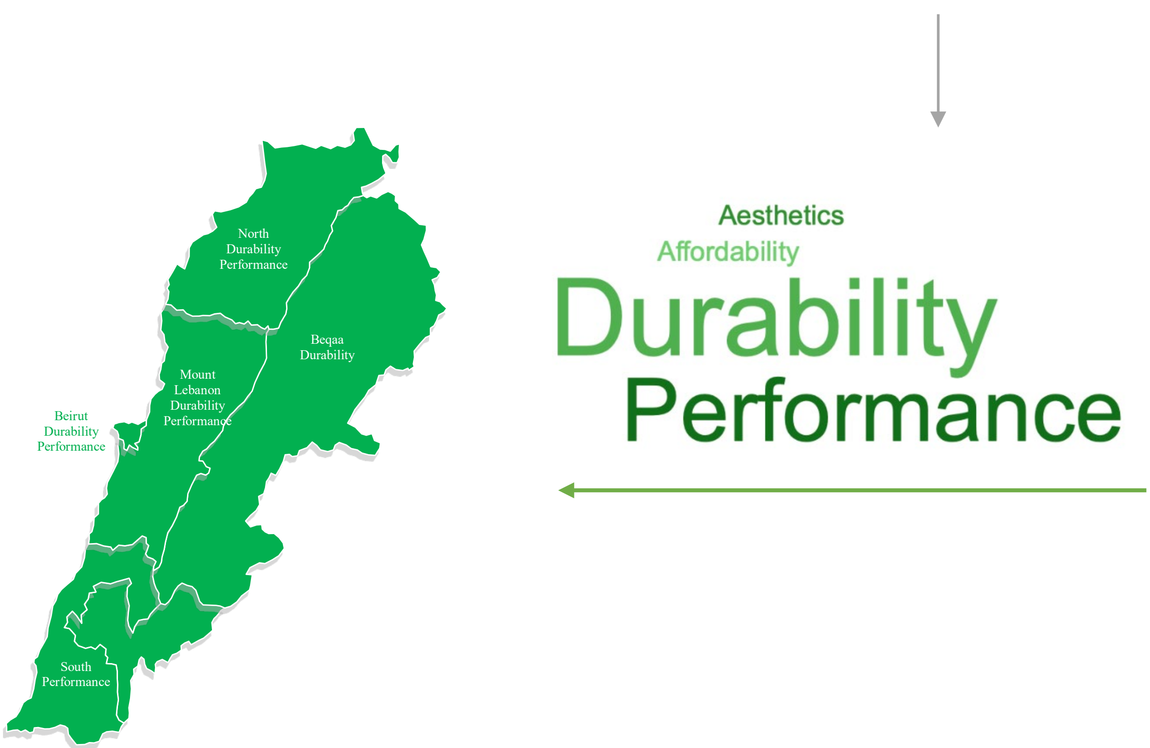

Figure 93. What's the most important feature in a home (Lebanon)?

Topic # 2: The Importance of Energy Efficiency in a Home

The second analyzed question asked respondents to rank the importance of energy efficiency in their home. Respondents were given the following options, very important, important, neural, slightly important, and not important at all. 82% of respondents (79% in US and 85% in Lebanon) stated that energy efficiency is either a very important or an important issue in their homes (Figures 94 & 95).

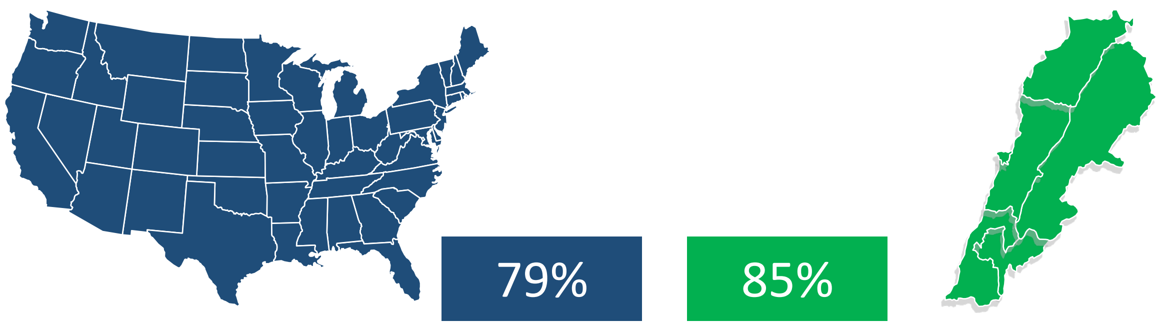

Figure 94. How important is energy efficiency in your home?

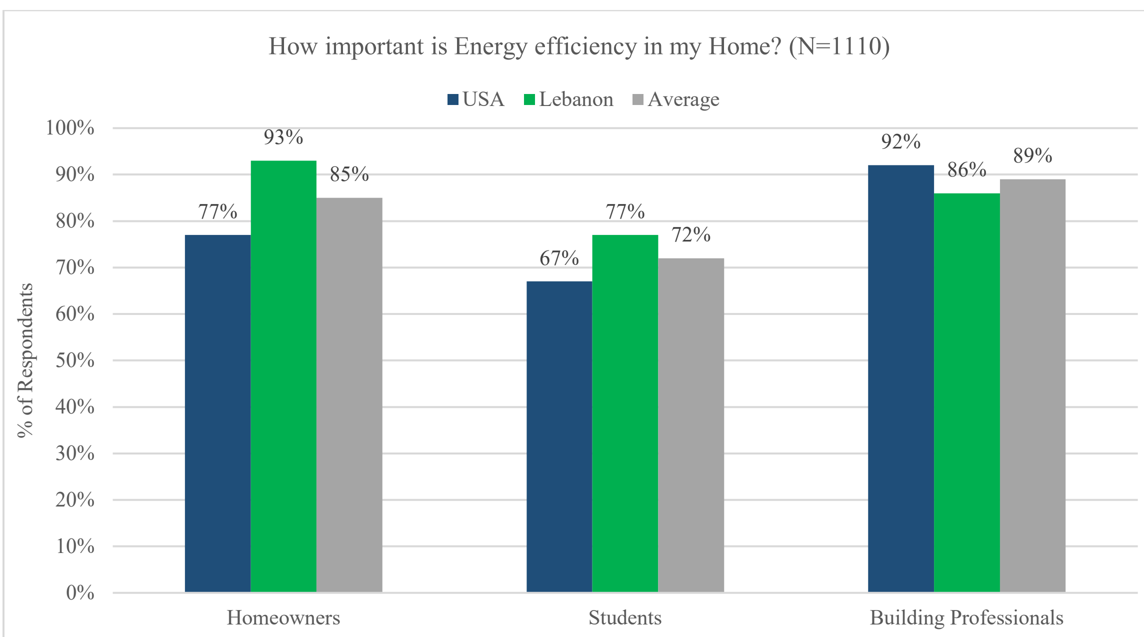

Figure 95. Importance of energy efficiency in a home based on category of respondents

Data analysis shows Michigan and California as the two highest states (percentage) ranking the importance of energy efficiency. Respondents from the Beqaa region in Lebanon had the highest percentage ranking the importance of energy efficiency (Figure 96).

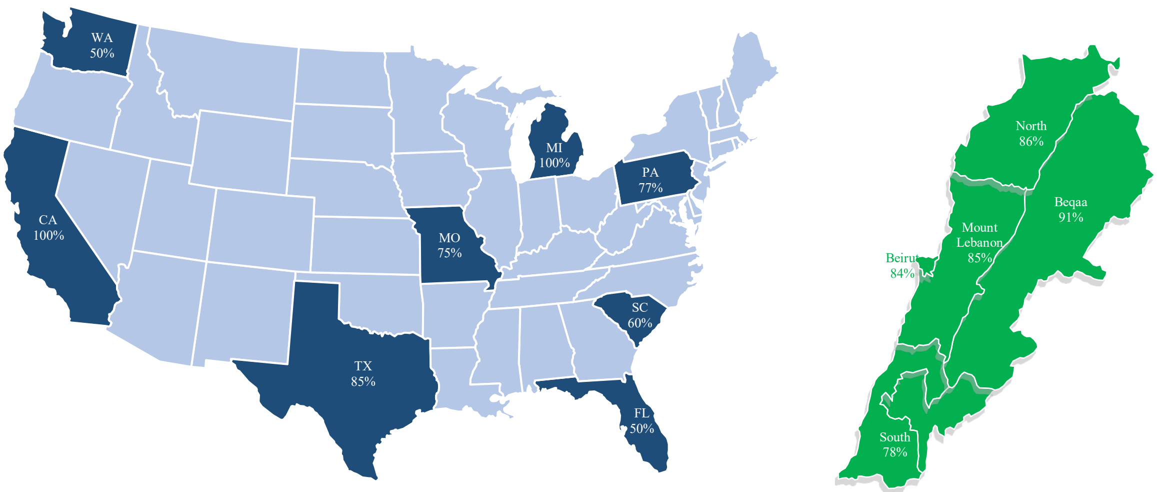

Figure 96. Importance of energy efficiency in a home based on State/Region (US & LB)

Topic # 3: Level of Familiarity with Zero Energy Homes

The third analyzed question asked respondents to state their level of familiarity with Zero Energy Homes. Respondents were given the following options, very familiar, familiar, neural, slightly familiar, and not familiar at all. Only 45% of respondents (41% in US & 48% in LB) indicted they're either very familiar or familiar with ZEHs (Figures 97 & 98). This question was critical to gauge respondent's knowledge and perception of ZEHs.

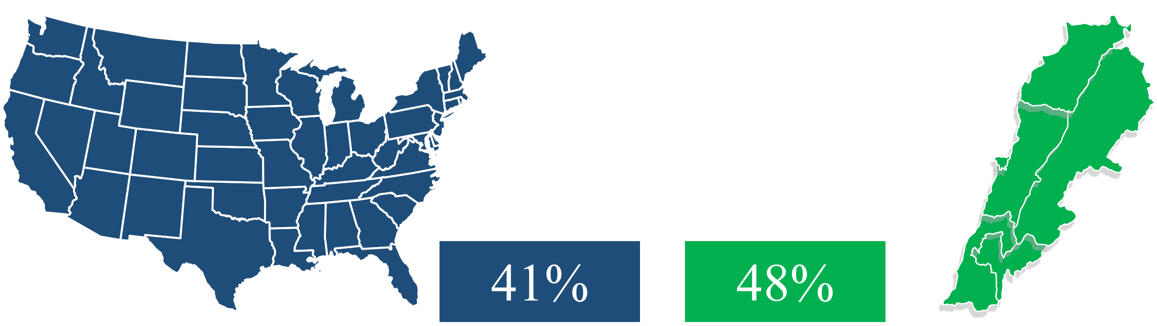

Figure 97. How Familiar are you with Zero Energy Homes?

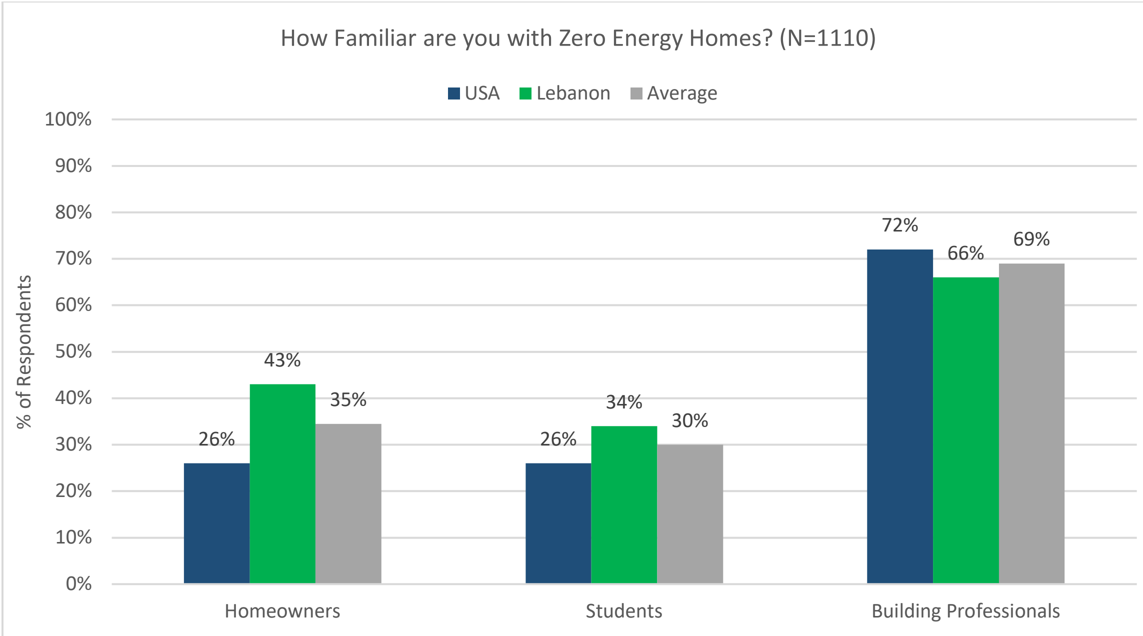

Figure 98. Familiarity with Zero Energy Homes based on category of respondents

Data analysis shows Florida, Michigan, and California as the three highest states (percentage) in terms of ZEHs familiarity. Missouri ranked the least familiar with ZEHs. Respondents from Northern Lebanon had the lowest level of familiarity with ZEHs. On the other hand, respondents from Mount Lebanon had the highest level of familiarity with ZEHs compared to all other regions in Lebanon (Figure 99).

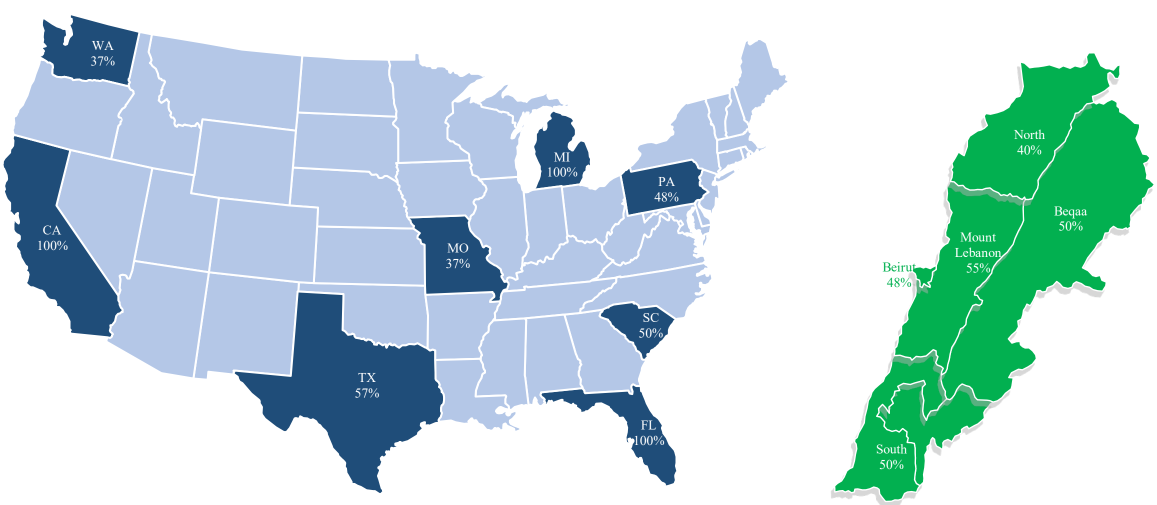

Figure 99. Level of familiarity with ZEHs based on State/Region (US & LB)

Topic 4: Level of Interest in Zero Energy Homes

The fourth analyzed question asked respondents to state their level of interest in Zero Energy Homes. Respondents were given the following options, very interested, interested, neural, slightly interested, and not interested at all. 78% of respondents expressed they are either very interested or interested in Zero Energy Homes (Figures 100). The highest level on interest came from homeowner respondents, followed by building professional and students. Furthermore, Lebanese respondents expressed a significantly higher intertest in Zero Energy Homes than their US counterparts. 93% of Lebanese homeowner respondents were either very interested or interested in Zero Energy Homes, compared to 68% of US homeowner respondents. Similarly, both Lebanese student and building professional respondents expressed a higher intertest in Zero Energy Housing. Overall, 86% of Lebanese respondents were interested in Zero Energy Homes compared to 69% of US respondents (Figure 101). Nonetheless, the level of interest in both locations is considerably high and significant. This indicates a high degree of willingness to embrace and adopt this sustainable and novel approach in the housing market. Furthermore, the survey results highlight a high level of interest from Lebanese respondents to the concept of Zero Energy homes as a new paradigm in the residential housing market.

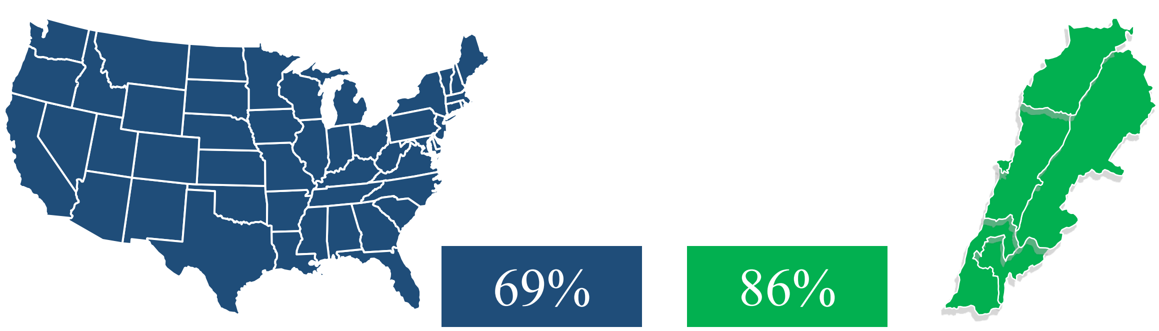

Figure 100. What’s your Level of interest in Zero Energy Homes?

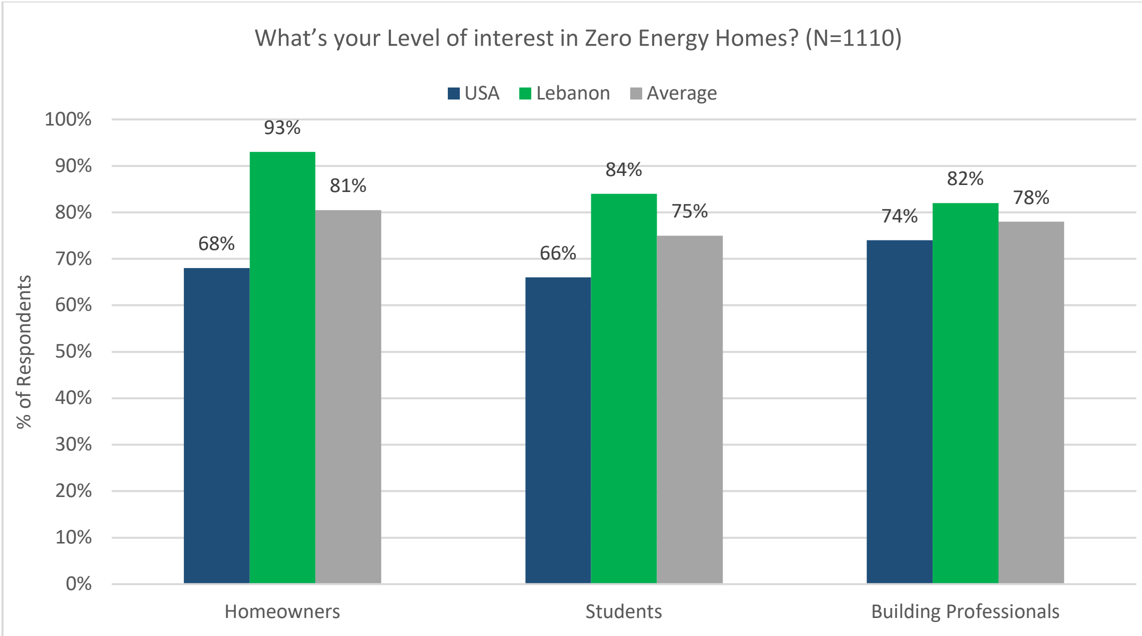

Figure 101. Level of interest in Zero Energy Homes based on category of respondents

California respondents expressed the highest level of interest Zero Energy Homes amongst US survey participants. Alternatively, Florida respondents expressed the least interest. Respondents from North Lebanon and Mount Lebanon had the highest interest in Zero Energy Homes, while the Beqaa region respondents expressed the least amount of interest amongst all Lebanese participants (Figure 102).

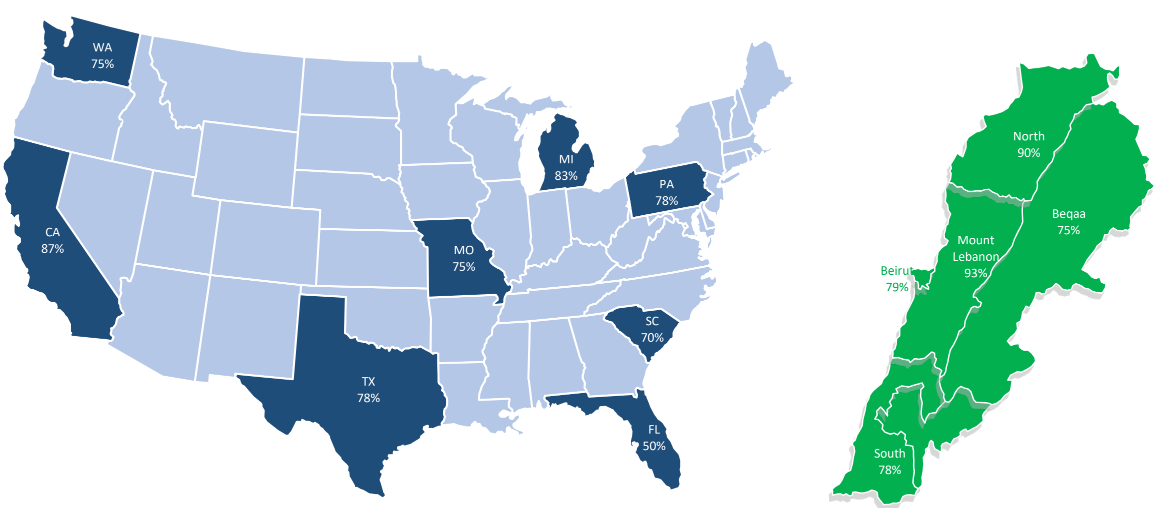

Figure 102. Level of interest with ZEHs based on State/Region (US & LB)

Topic 5: Perceived Barriers to Zero Energy Homes

The Fifth analyzed question gauged respondent's perceptions of barriers to Zero Energy Homes. Respondents were asked to discern which of the following options represented the strongest barrier to implementing and advancing the concepts of Zero Energy Homes: ZEHs cost, availability of skilled ZEHs contractors, ZEHs permitting, and the ability to build ZEHs in their jurisdiction. The question's Likert scale options were strong barrier, barrier, neutral, minimal barrier, and not a barrier. 74% of respondents (72% in US and 75% in Lebanon) selected availability of skilled Zero Energy Homes contractors/builders as strongest barrier, followed by cost at 72%, permitting at 35%, and the ability to build ZEHs at 25% (Figure 103). Access to skilled builders was perceived as the most significant barrier in both the US and Lebanon. Similarly, Zero Energy Homes cost was also seen as a noteworthy barrier. On the other hand, permitting and feasibility of building ZEHs were perceived as the least contributing barriers to advancing the concepts of Zero Energy Homes in both locations.

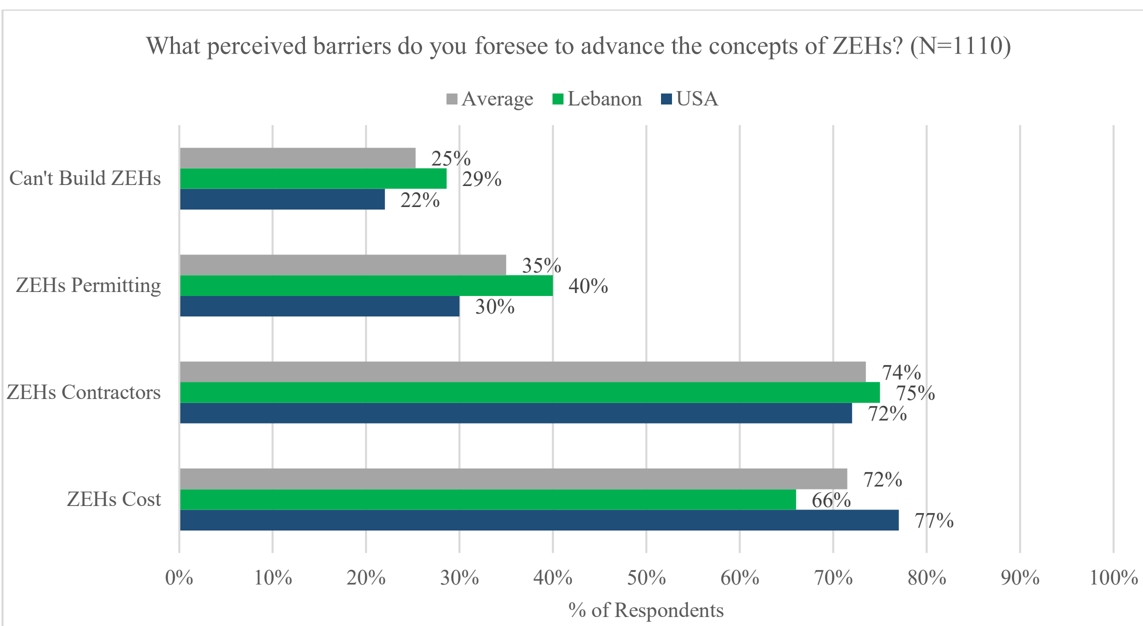

Figure 103. What perceived barriers do you foresee to advance the concepts of ZEHs?

US respondents from select States representing the various climate zones rated cost as the highest barrier toward the implementation of ZEHs followed by availability of skilled contractors (Figure 104). On the other hand, Lebanese respondents selected availability of skilled contractors as the highest barrier toward the adoption of ZEHs followed by cost (Figure 105).

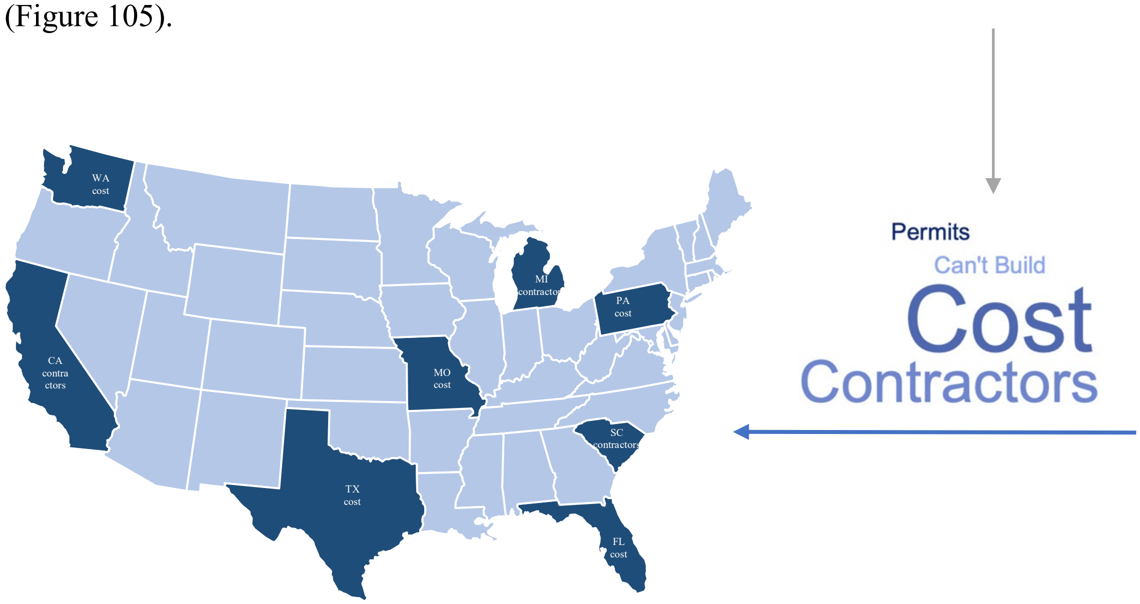

Figure 104. Perceived barriers to Zero Energy Homes (Certain US States)

Figure 105. Perceived barriers to Zero Energy Homes (Lebanon)

The survey also asked Lebanese respondents, from all three cohort categories, to evaluate several topics ranging from energy savings to climate change. These results were than compared to results from various US polls (Figure 106).

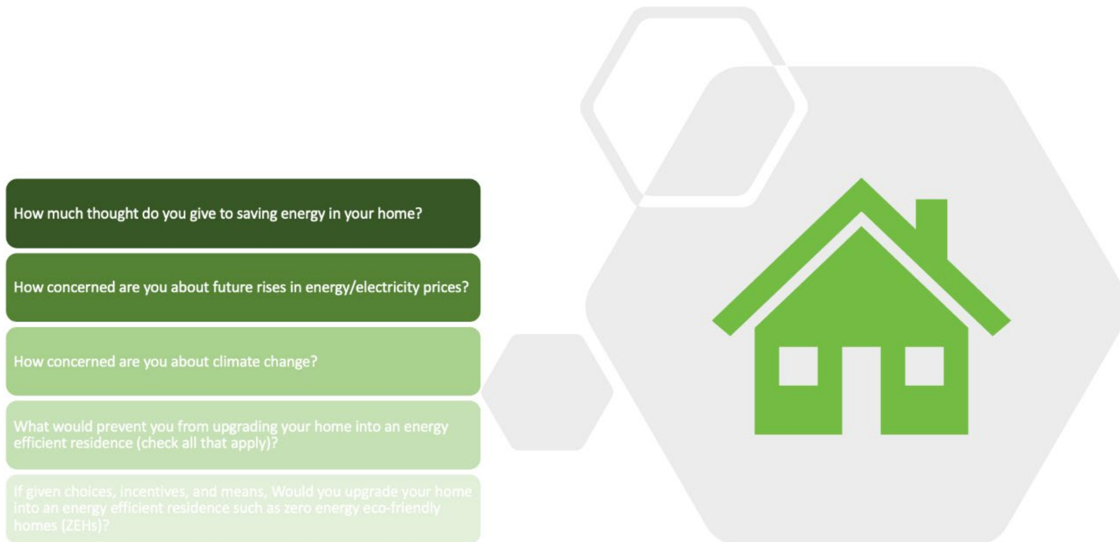

Figure 106. Lebanese-specific survey questions

Consideration of Saving Energy in your Home

Lebanese survey respondents were asked to rate how much thought they have given to saving energy in their place of residence. The following options were provided, a lot, a moderate amount, neutral, a little, and none at all. 33% of Lebanese respondents expressed that they've given a lot of thought to saving energy, 43% a moderate amount, and only 2% stated that they've never given a thought to energy saving in their home. Overall, 76% of Lebanese survey respondents expressed they have given moderate to significant consideration to saving energy in their homes, compared to 71% in the US based on a 2015 Triple Pundit poll. The same US survey revealed energy efficiency as America's most significant housing concern. Nonetheless, those significant results highlight the level of importance people give to saving energy in their home.

Concern about Rising Energy/Electricity Prices

Lebanese respondents were asked to assess their overall concerns about future rises in energy and electricity prices. The following options were provided, a lot, a moderate amount, neural, a little, and none at all. 86% of Lebanese respondents expressed some level of concern. Only 1% of survey respondents expressed no concern about rising energy and electricity prices. A Pew Research Center poll revealed 85% of US respondents expressed a concern about rising energy prices (Figure 107).

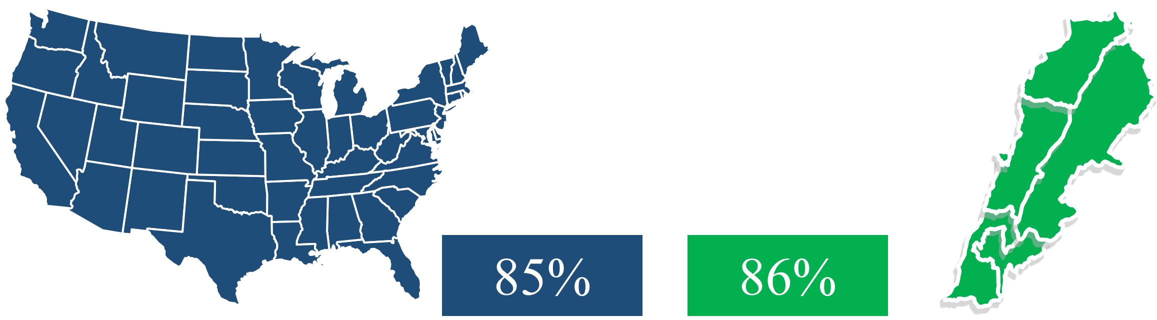

Figure 107. How Concerned are you about Rising energy/electricity prices?

Climate Change Concerns

Climate change is an existential threat to all populations. Its impacts are far reaching and non-discriminatory. Countries such as Lebanon are not immune to the adverse effects of climate change and are indeed very vulnerable to its impacts. Lebanon is highly susceptible to climate change, given its size, location, and overall socio-economic situation. Moreover, Lebanon has been chronically affected by severe droughts, heat wave, and extreme weather. Moreover, the country’s size and geographic location is highly vulnerable to climatic changes. To that end, the next survey question asked Lebanese respondents to rate their overall concerns about climate change. The following options were provided, a lot, a moderate amount, neural, a little, and none at all. 90% of Lebanese respondents expressed a moderate to high level of concern about climate change (Figure 108), with 62% of respondents expressing a high level of concern. Only 1% of Lebanese survey respondents expressed no concern about climate change. On the other hand, a PEW Research Center poll revealed 60% of US respondents to be concerned about climate change, up from 44% in 2009. While climate change remains a polarizing issue amongst most Americans, Lebanese citizens view it as an existential threat to their overall well-being and livelihood.

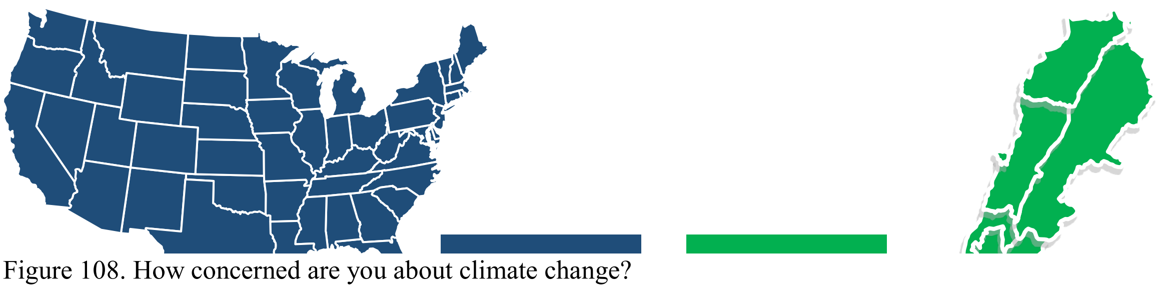

Figure 108. How concerned are you about climate change?

Barriers to Upgrading into an Energy Efficient Home

The next question asked Lebanese respondents to select and rank barriers that prevent them from upgrading their home into an energy efficient residence. The following barriers were provided as options to choose from: financial implications/strain, economic instability, availability of skilled contractors, unstable political situation, knowledge gap, and lastly not a priority to upgrade into an energy efficient home. 78% of Lebanese respondents selected financial implications and strain as the most significant barrier towards implementing energy conservation measures in their home. Alternatively, the *Not a Priority* option was the least selected choice at 14% (Figure 109). Not surprisingly, economic and political instability also ranked high in terms of potential barriers to energy efficiency efforts. Nonetheless, respondents seemed to be most wary of the implied and perceived cost burden energy efficient upgrades might pose on their bottom line. It's therefore imperative to clearly explain the net benefits and quick return on investment such green upgrades would generate and bring to bear.

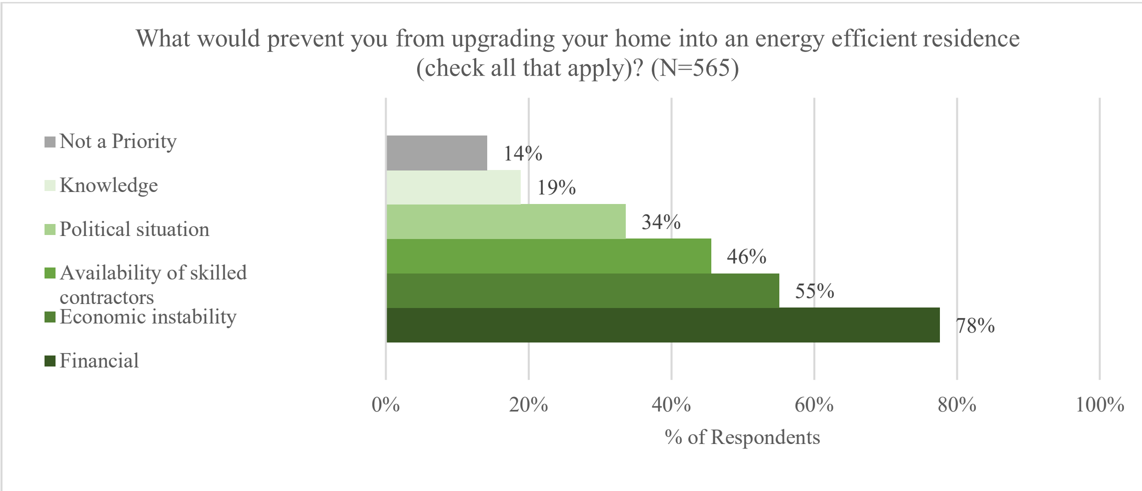

Figure 109. Barriers to Upgrading into an Energy Efficient Home

Upgrading to an Energy Efficient Home

The last question asked Lebanese respondents to indicate whether or not they would be willing to upgrade their home into an energy efficient residence, given choices, incentives, and means to do so. Overwhelmingly, 81% of respondents stated they would be inclined to implement energy conservation measures and upgrades in their homes (Figure 110).

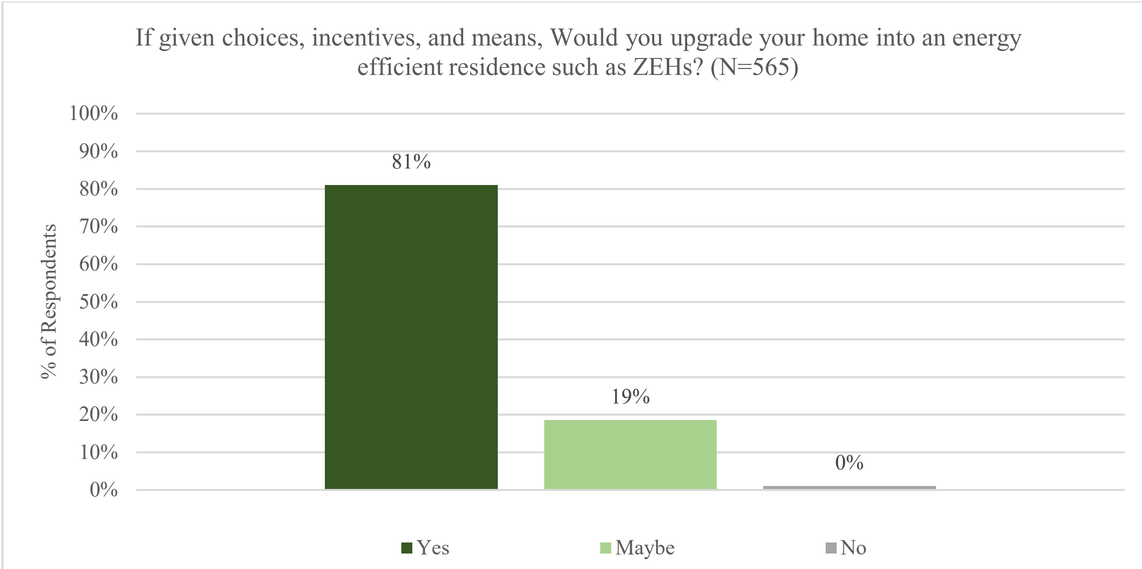

Figure 110. Would you upgrade into an Energy Efficient Home?

Discussion

When asked about the most important feature of a home, overall collective survey responses from the US and Lebanon were quite similar. However, more variances appeared when analyzing the three sample cohorts independently. For example, Lebanese homeowners rated both home performance and aesthetics significantly higher than their US counterparts. On the other hand, US students ranked home performance and affordability higher than Lebanese students. Similarly, US building professional respondents rated home performance higher than their Lebanese counterparts. When asked about the importance of energy efficiency in their home, a higher percentage of Lebanese homeowners and students considered it so than did US respondents. On the other hand, more US building professionals considered energy efficiency as an important aspect of one's home than Lebanese professionals. Collectively, building professionals rated the importance of energy efficiency in a home higher than both homeowners and students. When asked about familiarity with Zero Energy Homes (ZEHs), both Lebanese homeowners and students expressed a higher rate of familiarity with the concept than US respondents. However, more US building professionals stated a higher level of familiarity than their Lebanese counterparts. Cumulatively and not surprisingly, building professionals had double the rate of familiarity with ZEHs than students and homeowners. When analyzing survey results of respondents' level of interest in Zero Energy Homes, Lebanese respondents across all three sample cohorts expressed a higher rate of interest than US respondents. Furthermore, Lebanese homeowners had the highest interest amongst all other cohorts at 93%. When asked about barriers to implementing the concept of ZEHs, all three Lebanese cohorts selected availability of skilled contractors as the most significant barrier. On the other hand, US homeowners, students, and building professionals all considered cost as the most significant barrier towards the application of ZEHs. Thereafter, respondents were asked to rate the most helpful measures to advance the adoption of ZEHs, including building codes, education and awareness, financial incentives, and legislative action. US respondents, collectively and individual cohorts, rated financial incentives as the most helpful measure in advancing the concepts of ZEHs. Lebanese respondents selected educational and awareness campaigns as the most helpful measure, followed very closely by financial incentives. Individually, Lebanese homeowners ranked financial incentives slightly higher than educational awareness at 94% and 93% respectively. On the other hand, 87% of Lebanese students elected education and awareness as the most helpful measure. 91% Lebanese building professionals selected both educational awareness and financial incentives as the most helpful measures to advance ZEHs. Interestingly, but not surprisingly, Lebanese respondents collectively rated legislative actions (82% LB vs 65% US) and building codes (80% LB vs 72% US) higher than their US counterparts. This is reflective of the current environment in Lebanon that lacks robust performance-based building codes as well as weak legislative frameworks.

Survey results show a clear energy perception gap that needs to be addressed effectively to successfully advance energy efficiency in the residential market to combat climate change and excessive energy consumption. To that end, an overwhelming 90% of Lebanese respondents and 60% of US respondents expressed serious concerns about climate change. It's therefore paramount we explore robust energy conservation and efficiency measures to circumvent those alarming trends in energy consumption, especially in non-OECD countries like Lebanon. However, survey results point to a significant knowledge and perception gap in energy efficiency and Zero Energy Housing (ZEHs). Bridging that gap is critical in proliferating effective energy conservation measures and climate change mitigation initiatives. Furthermore, survey findings show a significant lack of knowledge and familiarity regarding energy efficiency and ZEHs; and despite most US and Lebanese survey respondents stating that energy efficiency is an important aspect in their place of residence, less than half were familiar with the concept of Zero Energy Homes. However, most survey respondents expressed high interest in ZEHs as an alternative housing option once introduced to the concept and benefits of ZEHs. More than 85% of Lebanese respondents and 65 % of US respondents expressed a high level of intertest in ZEHs. ZEHs are a critical component of advancing a sustainable, resilient, and equitable energy future, especially in non-OECD countries such as Lebanon. Most respondents ranked home performance and durability as the most important features of a home, indicating a level of awareness regarding current energy consumption patterns. To that end, more than 70% of respondents stated they've given a considerable amount of thought to saving energy in their home. Survey responses regarding concerns about rising electricity and energy prices affirm respondents' interest in energy saving and efficiency. However, most respondents perceived ZEHs cost and availability of skilled contractors as major barriers and obstacles in advancing and adopting the concepts of Zero Energy Homes. Hence, that perception gap, as a result of knowledge deficits and common misconceptions, is an impeding roadblock in the proliferation of widely adopted robust energy conservation and efficiency measures. Survey results clearly show that people are worried about climate change and its implications, have given considerable thought to saving energy in their homes, have rated energy efficiency in their homes as an important component, and are interested in Zero Energy Homes as a new housing paradigm. Despite all of that, their knowledge and familiarity with ZEHs and energy efficiency was very low.

Conclusion

Buildings have a significant impact on energy use and the environment, accounting for approximately 20% of global energy consumption in 2018 (EIA). These global consumption trends are driven primarily by increasing electricity demand in residential and commercial buildings. The U.S. Energy Information Administration predicts that rising living standards and populations in non-OECD (Organization for Economic Co-operation and Development) nations, including Lebanon, will lead to a significant rise in electricity demand globally (EIA, 2017). To that end, the EIA's 2019 International Energy Outlook projected an average 2% per year or more in global energy consumption growth in buildings from 2018 to 2050 in non-OECD countries, compared to 1.3% per year in OECD countries. EIA anticipates that total building electricity consumption in non-OECD countries will exceed that in OECD countries in the early 2020s. Moreover, buildings in non-OECD nations will collectively consume twice as much electricity than buildings in OECD countries by 2050. In the United States, the residential building sector consumes more than half of the total primary energy attributed to the building sector (EIA, 2017). The building sector in Lebanon is one of the major drivers of energy consumption and associated air pollution, consuming approximately 30-40% of the total generated electricity. It’s paramount we explore robust energy conservation and efficiency measures to circumvent those alarming trends in energy consumption, especially in non-OECD countries like Lebanon. Survey findings show a significant knowledge and perception gap in energy efficiency and Zero Energy Housing. Bridging that gap is critical in proliferating effective energy conservation measures and climate change mitigation initiatives. Therefore, concerted efforts need to be spent educating, promoting, and providing access to energy efficiency and ZEHs best practices and strategies. It’s imperative that homeowners, students, building professionals, and all other concerned parties be enabled to take action toward energy efficient housing. Survey results were instrumental in providing a foundational knowledge base for energy efficiency and Zero Energy Housing perceptions. The results will be used to shape and direct the narrative to address energy efficiency perception gaps in Lebanon to advance the concept of Zero Energy Housing. It’s the aim of this project to advance the development of robust and systematic Zero Energy guidelines and strategies that could be effectively adopted in multi-level residential apartment buildings in Lebanon.

Chapter 5: Preliminary Baseline Modeling Results

Introduction

Lebanon is heavily reliable on imported fossil fuels for most of its energy generation needs. The nation chronically struggles to meet its power consumption needs due to growing demand, insufficient production capacities, and outdated antiquated power generation utilities. Moreover, climate change, unchecked urbanization, and a population boom have all exacerbated the energy-power shortage crisis. As a result, Lebanon is expected to exceed its 2010 energy consumption by 250% in 2030 (Yathreb, 2016). The primary driver of that projected increase in energy consumption is the deficient performance of existing residential apartment buildings due to the lack of robust energy efficiency measures and practices. To that end, residential buildings in Lebanon account for approximately 47% of total energy consumption, by far the largest energy end user in the nation. As such, interest in building energy efficiency and performance has increased in the past decade especially in the commercial building sector. Nonetheless, energy conservation measures within the residential building sector remains primitive and intermittent. Furthermore, there's a severe lack of accessible data pertaining to energy performance and consumption in standard residential apartment buildings. The absence of an energy consumption central database for residential buildings is a significant hurdle towards achieving Net Zero Energy. It's imperative to establish a baseline metric for energy use in residential buildings to better understand energy consumption patterns, and thereafter, successfully propagate robust energy conservation and efficiency measures. To that end, a building performance simulation model was created to establish an average energy consumption baseline for a standard Lebanese apartment building block. The established baseline model utilized the

Cove Tool energy modeling simulation platform to predict energy consumption for cooling, heating, domestic hot water, lighting, and other significant energy end-use systems, as it relates to the building's layout, footprint, massing, and construction specifications. The result of the energy simulation process is a modeled benchmark energy use intensity (EUI) baseline metric for a standard residential apartment building. The study aimed to establish and develop a representative residential EUI benchmark for existing residential buildings in the Lebanese residential sector, to better guide and inform the research towards the adoption of robust energy efficiency practices and strategies. The established base model will serve as a foundational baseline towards the goal of achieving Net Zero Energy-ready buildings. Such a benchmark would benefit various stakeholders, including homeowners been made more aware of energy use patterns. It would also assist public agencies, code developers, and industry professionals in formulating more effective measures to reduce energy consumption and its associated impacts on the environment.

Background

The Climate of Lebanon can be classified as Csa climate, a mild Mediterranean climate, characterized by hot dry summers with minimal precipitation and cool wet winters. Lebanon has four distinct climate zones. Zone 1 is the coastal zone, where 70% of the Lebanese population lives. Climate change, manifested through rising sea levels and increasing temperatures, is a major issue in the country and is projected to affect the densely populated coastal urban areas that includes the country's main infrastructure and most of the population. As such energy consumption patterns are heavily affected by climate variations.

Lebanon is an energy intensive country, exceeding many neighboring southern Mediterranean nations. Moreover, energy consumption patterns have been increasing over the past decade and are projected to continue to grow over the next 10 years. To that end, Lebanon primarily uses imported liquid petroleum gas to meet more than 90% of its primary energy needs (Azar, 2010). Lebanon has one power utility, seven thermal power plants (3 operate on heavy fuel oil and 4 on gas). 96% of the electricity is generated through thermal plants, which generated 12,237 GWh in 2015, far below the demand of 20,368 GWh (Lebanon Ministry of Environment, 2020). As a result, Lebanon experiences chronic power outages. This gave rise to an unorganized and unregulated private generation sector that provides anywhere between 30 and 40% of the needed power. Lebanon's electricity sector has been plagued by corruption, inefficiencies, and monopolies. As such, residents turn to neighbourhood power-generator services to cover the remaining hours of the day. Electrical residential demand increased from 3,080 GWh in 2009 to 5,750.8 GWh in 2014 (LCEC, 2018). Residential electrical demand is largely composed of cooling and dehumidification, ventilation, lighting, and domestic hot water. Nonetheless, sustainable residential construction remains primitive and severely deficient. Most residential buildings are not properly insulated (Yathreb, 2016). This is directly attributable to the fact that none of the thermal insulation standards were ever adopted and remain primarily voluntary (EL Andaloussi, 2011). Similarly, the role of governmental and public agencies in promoting sustainable development is not adequately established yet. Residential energy consumption patterns are heavily affected by the absence of robust energy conservation measures and practices.

The Lebanese population is highly urbanized, with an estimated 70-90% of the population living in major urban centres. Most citizens live in standard multi-story residential apartment blocks, accounting for approximately 70% of the residential market in 2012 (BankMed, 2014). Apartments blocks comprised about 67% of Lebanese households. 55% of these dwellings were built 25 years ago or older. The average apartment size is between 100 and 200 m^2. Most apartment blocks are built for profit to meet basic standards with minimal attention to performance, efficiency, and comfort. Residential energy consumption is relatively high compared to regional nations with similar climate. The Per capita residential consumption is around 1727 kWh, placing Lebanon among the highest consumers of electricity in Western Europe and neighbouring countries. At the low end, the annual energy consumption of a typical multi-story residential building is approximately 135-148 kWh/m^2/yr (Mortada, 2018). At the high end, the annual energy consumption averaged between 178 kWh/m^2/yr and 220 kWh/m^2/yr (Ghaddar, 1998). An average EUI of 184 kWh/m^2/yr was calculated and adopted as the existing EUI for benchmarking purposes. Anemic legislative and institutional framework, lack of enforcement mechanisms, absence of green construction legislation, subsidies of energy prices, and the absence of a national energy strategy have all contributed to a minimal adoption of energy efficiency measures and policies in the residential building sector, leading to ramped high energy consumption patterns (Mourtada, 2008).

Methods

The research focused on assessing and evaluating energy performance and consumption patterns in a standard Lebanese residential apartment building located in climate zone 1. The target market was middle to low-income housing apartment blocks, which constitute most residential archetypes in the country. Typological data was collected via surveys, questionnaires, and literature review. The study employed two main steps to determine and establish a baseline energy consumption benchmark for a standard residential apartment building block. The first step identified and determined, through literature review and questionnaires, the characteristics and typology of a standard Lebanese residential apartment building. Based on that information, a baseline building model was modeled using the *Sketchup* building modeling platform. Thereafter, the second step entailed developing a representative energy benchmark model to generate a baseline EUI, to be compared against the existing and industry-set EUI benchmarks. For this step, the building model was exported to an energy simulation platform to assess and establish its baseline energy consumption. The Cove Tool energy modeling platform, an automated design platform for intelligent building performance and parametric optimization, was used to evaluate and establish baseline energy use for the modeled apartment block on an annual basis.

The research employed a quantitative energy modeling and simulation approach to establish an energy consumption model baseline EUI in a standard Lebanese apartment building. The baseline model utilized normalized energy and construction specifications with appropriate climate and location data. To normalize the data, a baseline benchmark model was developed addressing the following components: building size/footprint, number of floors, apartment size, construction specifications (envelope, HVAC, Windows, insulation values, etc.), household number, and number of bedrooms and bathrooms. The EUI metric, a measure of annual energy consumed by a building per unit of gross floor area, was used as the main energy performance indicator. All baseline energy simulation assumptions were based on building code guidelines and common construction practices. The modeling and simulation protocols were consistent with industry references and guidelines. All baseline standard architectural and energy systems specifications were adopted from industry standards, construction norms, and literature review (Order of Engineers and Architects, 2010).

Baseline Building Characteristics & Energy Model Parameters

The building chosen for this analysis was a representative hypothetical standard multi-level multi-family apartment building, located in Amioun Lebanon within climate zone 1. The location was chosen due to the growth and prevalence of apartment building construction in that specific region and equivalent. The building typology is representative of a typical middle to low-income Lebanese apartment block. The building has a flat roof with a square footprint consisting of 4 floors and 8 total apartments, 2 per floor (Figure 111). The building footprint measures 20m x 20m with a total gross area of $1600m^2$. Each apartment has an area of $175m^2$, consisting of a living room, dining room, kitchen, 3-4 bedrooms, 3 bathrooms, and minor ancillary spaces. The building construction is a reinforced concrete frame system with hollow concrete masonry blocks as infill, building envelope, and interior walls. Glazing systems are composed of single pane clear windows, 3mm in thickness with aluminum frames. Floor to ceiling height was determined to average between 2.85m and 3m. Household occupancy was set to 4 people, which is typical of a Lebanese family.

Figure 111. Images depicting the design and layout of a typical Lebanese residential apartment block

The energy model parameters were determined based on survey results and an extensive literature review of industry practices and reference codes of five main categories: cooling and heating intensities, domestic hot water, lighting, and plug loads.

Cooling Load Intensity. Most Lebanese use air-conditioning window split units (ACs) as the primary source of cooling in their home. These units are usually placed in living spaces and bedrooms primarily. The peak operation time of AC use is June through August, and especially during the evening and nighttime hours. Fans are also used when power doesn't permit the use of ACs and during the spring season (Yathreb, 2016). Amioun, the designated location of the study has 362 Cooling Degree Days (CDD).

Heating Load Intensity. Most Lebanese use electric heaters for space heating. To that end, 80% utilized some form of electrical heating, while 20% used gas or diesel (Yathreb, 2016). The heating season in Lebanon runs from November to March. Heating systems are employed daily, with heavier use during the afternoon and evening hours. Amioun has 696 Heating Degree Days (HDD).

Domestic Hot Water (DHW). Most Lebanese use electric-tank heaters for water heating. 10% and growing are now utilizing solar thermal for water heating purposes (Yathreb, 2016). Water heating is used mostly for clothe washing, dish washing, cooking, and showers. The average DHW use is estimated around 5 L/m^2 per day during the summer and 21 L/m^2 per day during the winter season (Yathreb, 2016).

Lighting. The two primary light bulb typologies are compact fluorescent (CFL) and incandescent lamps. The average lighting power intensity is around 28 W/m^2 (Yathreb, 2016).

Plug Loads. Most apartment appliances and plug-in equipment are considered energy intensive. The average plug load peak power intensity is estimated around 52 W/m^2 (Yathreb, 2016).

The Cove Tool energy modeling platform was used to evaluate and establish baseline energy consumption and the representative EUI benchmark. It's paramount a baseline EUI is set and determined to effectively explore robust Net Zero Energy strategies in future developments and practices. Code-referenced standards, industry practices, and literature review for standard apartment buildings were used to establish construction and thermal parameters for the baseline energy modeling process (Order of Engineers and Architects, 2010) (Table 6).

Table 6. Thermal and construction parameters of the typical modeled building

Category	Baseline Energy Model Specifications
Total Building Area	1600m^2 total Gross Area
Floor Area	400m^2 per Floor
Roof Area	400m^2
N of Floors & Building Height	4 Floors at 12.60m total height
Number of Apartments & Size	8 (2 per floor) @ 175m^2 per apartment
External walls U-Value	0.541 W/m^{2}K
Roof U-Value	1.66 W/m^{2}K
Internal floors U-Value	1.367 W/m^{2}K
Internal doors U-Value	1.852 W/m^{2}K
External Glazing/Openings	U-Value @ 5.8 W/m^{2}K - WWR @ 20% - SHGC @ 0.75 - SC @ 0.86 - TVIS @ 0.74 - Shading None
Cooling System	Plugin provisional air conditioning window split units (COP 3)
Heating System	Plugin electric heaters (COP 0.85) OR Diesel furnace/boiler via hot water pipes (Chauffage)
Hot Water System	Electric, Tank @ 15 L/m^2 per day
Construction Typology	Heavy weight reinforced concrete skeleton/frame
Wall Systems	Single 15cm (6") CMU construction system with no insulation
Floor & Roof Typology	Flat un-insulated 15cm concrete slab, 2.5 W/m^{2}K
Wall Area	890.2m^2
Glazing Area	139.1m^2
Glazing Systems	Low-performance single pane windows, 15% WWR

Results

The energy simulation run utilized the Cove Tool to generate a benchmark EUI metric for a standard Lebanese multi-family apartment building block. The baseline model was simulated using ASHRAE 2007 - IECC 2009 Equivalent energy code assumptions. The baseline energy modeling run yielded an EUI of 191.3 kWh/m^2/yr (60.6 KBtu/sf/yr), which is equitable with the actual national average EUI of 184 kWh/m^2/yr (58 KBtu/sf/yr) for standard Lebanese multi-family apartment buildings (Yathreb, 2016). However, the modeled EUI was 53% higher than the 2030 baseline benchmark EUI and 665% higher than the 2030 Target EUI (Figure 112). Similarly, the simulated EUI was higher than the on-site surveyed EUI of 135 kWh/m^2/yr (42 KBtu/sf/yr) to 148 kWh/m^2/yr (46.9 KBtu/sf/yr), set by 2013 and 2015 national studies defining energy demand for standard Lebanese residential buildings (LCEC, 2018) (Figure 113). This high EUI could be attributed various factors including lack of thermal insulation, inefficient HVAC and hot water systems and a narrow comfort range (using AC and heat when not necessary).

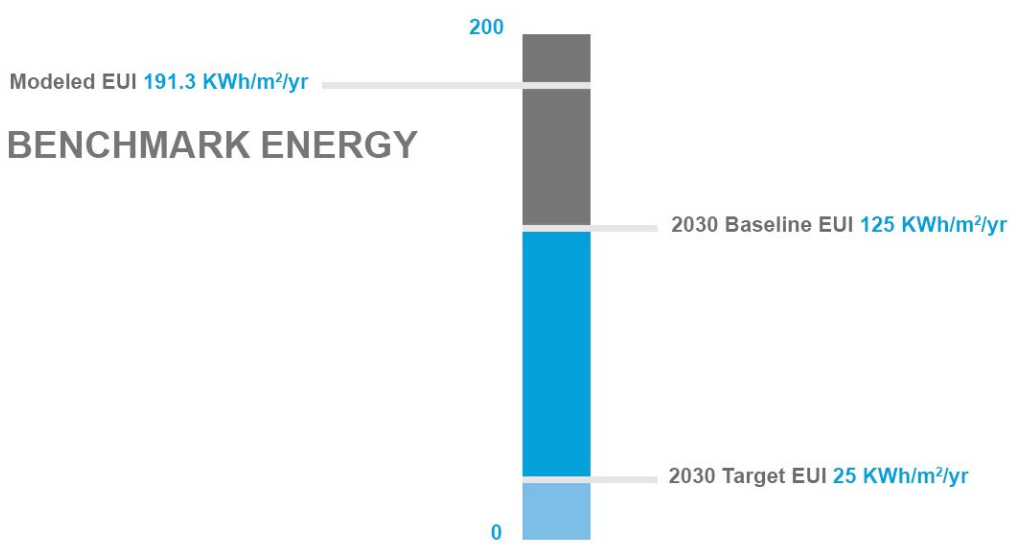

Figure 112. Chart depicting the baseline modeled EUI in reference to 2030 EUI benchmarks

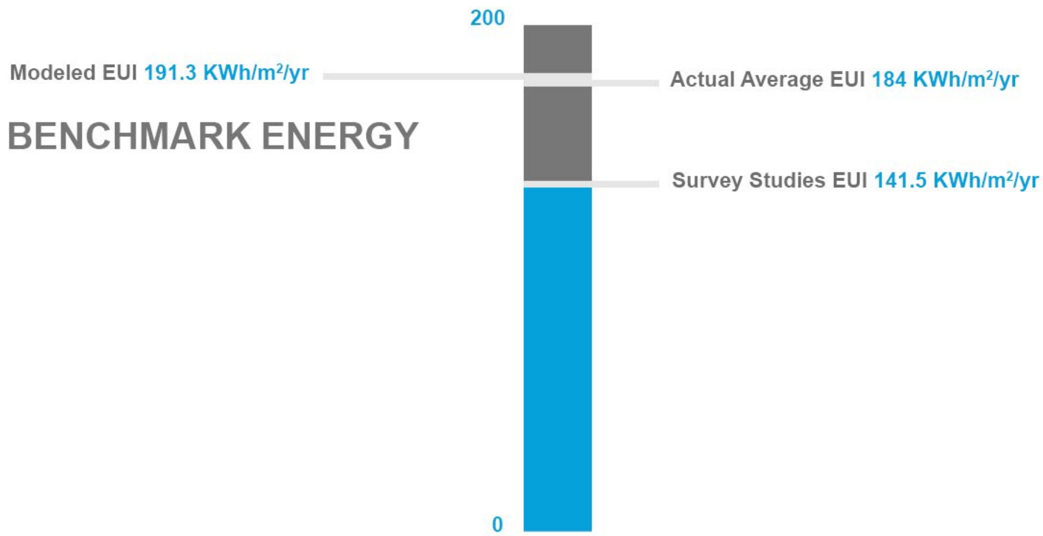

Figure 113. Chart depicting the baseline modeled EUI in reference to other Lebanese EUI benchmarks

The modeled baseline apartment building emitted 92.5 Tonne of Carbon Dioxide annually compared to the 2030 baseline of 60.3 Tonne/CO_2e/yr, equivalent to CO_2 emissions from 99,697 pounds of coal and electricity consumed by 16 homes (Figure 114). Space conditioning loads (cooling and heating) constituted the largest energy end users in the modeled baseline condition, followed by lighting and equipment loads, emblematic of the Building's weak thermal envelope and lack of thermal insulation (Figure 115). The modeled data tracked relatively closely with actual averages of energy end-use EUI data from an existing multi-family apartment building in the same location and region of the study. The equipment component of energy end use consumption is a significant driver of energy use in Lebanese households reflected in both data sets. Those loads are affected heavily by cultural and behavioral patterns of electricity consumption due to significant growth in equipment rate including cooking patterns and household appliances (TVs, information and communication technologies-ICTs, refrigerators, heaters, fans, etc.).

Figure 114. Annual Carbon Dioxide emissions equivalencies for the modeled apartment building

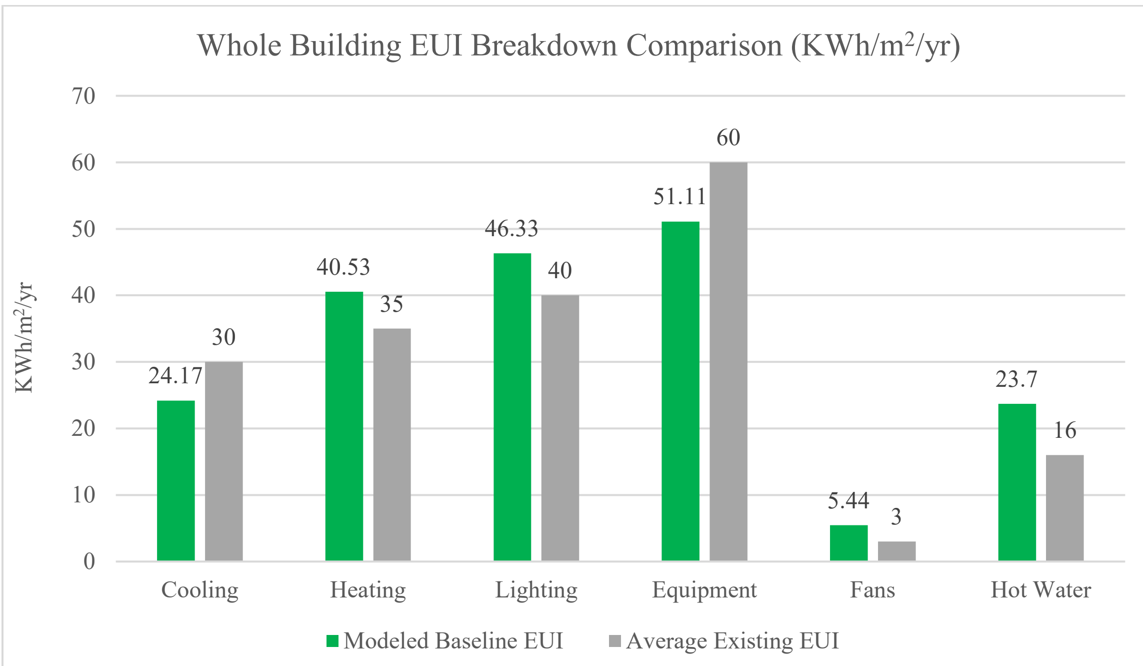

Figure 115. Modeled and Existing annual whole building EUI end-use breakdowns

The baseline energy modeling run generated an adaptive comfort profile that indicates a high-temperature risk during the daytime hours (Figure 116). Nonetheless, the results of the psychrometric chart show passive adaptive strategies are well suited to mitigate excessive heating and cooling loads, and hence increase overall thermal comfort (Figure 117). Similarly, wind rose diagrams show ample amount of prevailing wind available for passive cooling (Figure 118).

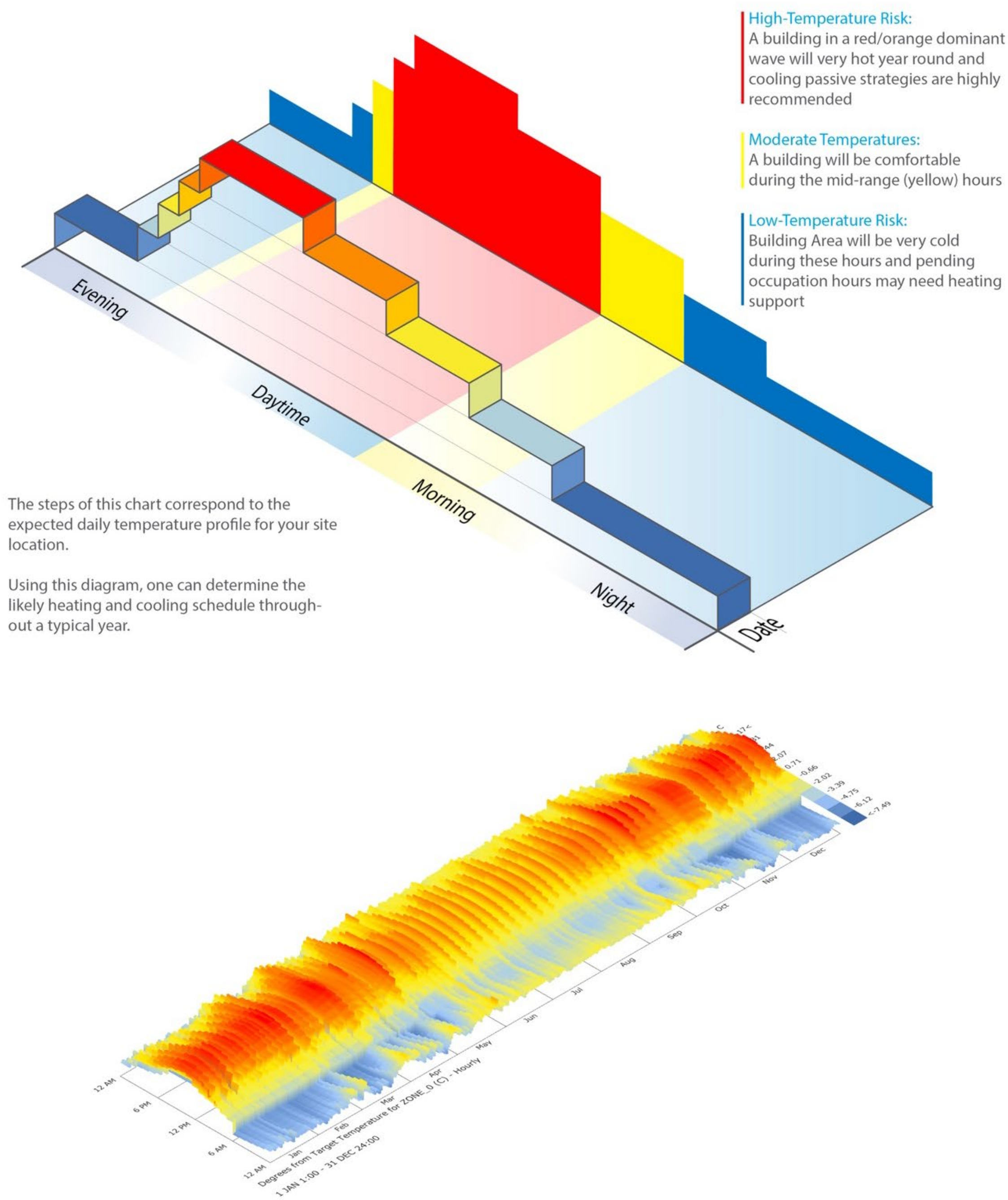

Figure 116. Baseline adaptive comfort charts highlighting annual temperature profile

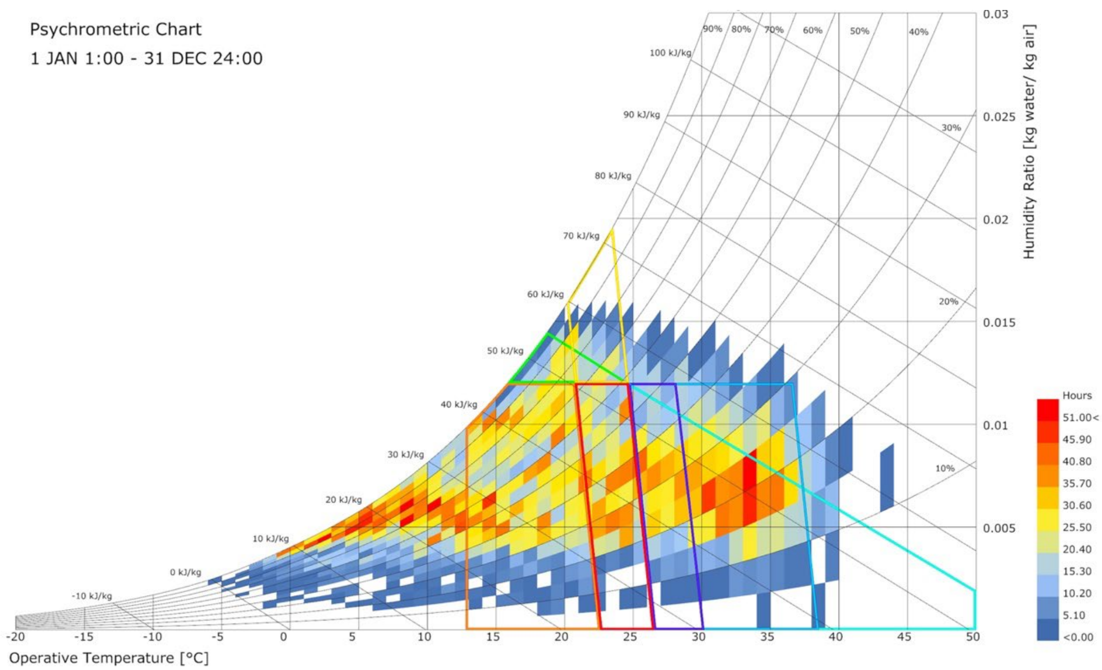

Figure 117. Chart showing the relationship between dry bulb, humidity ratio, and enthalpy

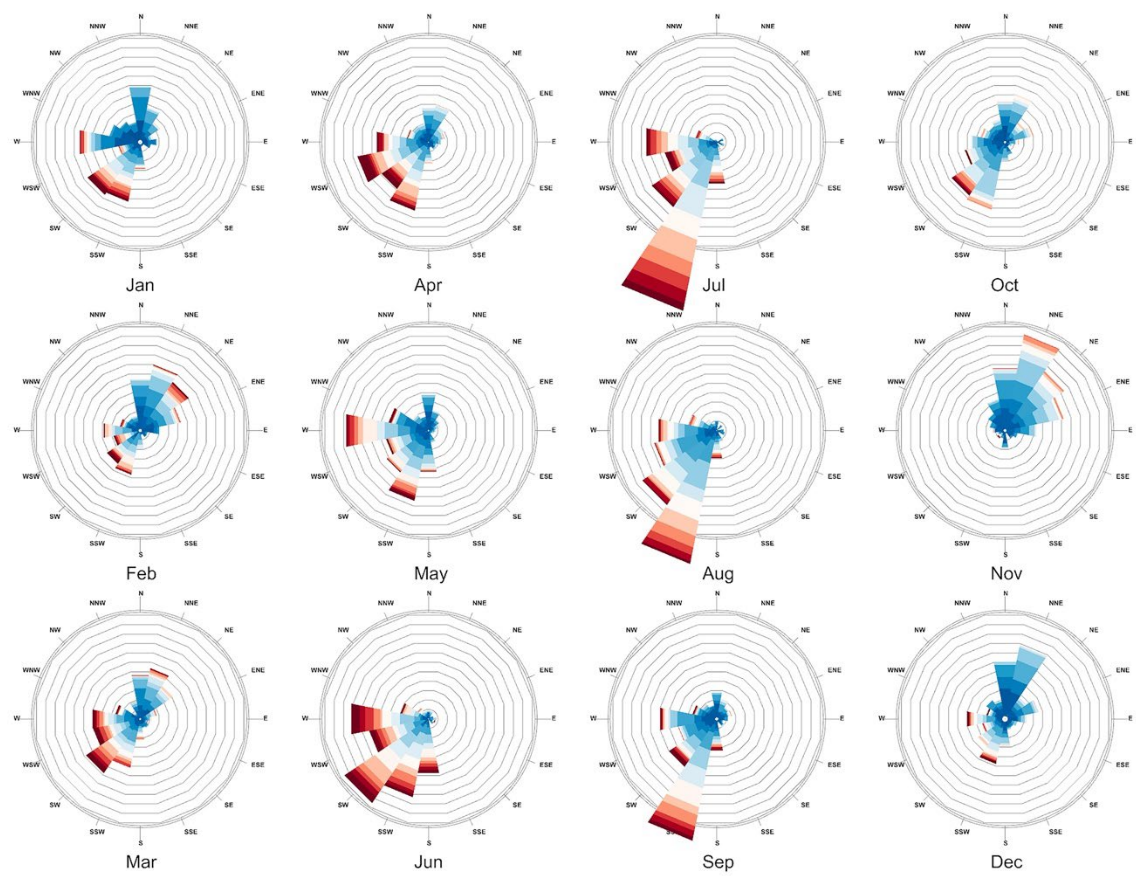

Figure 118. Wind diagrams showing the wind direction and intensity coming to the site

Discussion

The accuracy of the baseline energy modeling results was validated by the research data on actual EUI averages reported by industry and non-governmental agencies. To that end, the simulated EUI was only 3.9% higher than the reported existing EUI, and hence was in line with actual data trends and patterns. Nonetheless, the baseline simulation results do show significantly higher energy consumption than prescribed by the 2010 Lebanese Thermal Standard and Net Zero Energy EUI targets. By comparison, the baseline modeled EUI of 191.3 KWh/m^2/yr was 20.4% higher than that of the EU average at 158.8 kWh/m^2/yr (Eurostat, 2020). Moreover, the simulated EUI, representative of existing and conditions, was 35% higher than the average EUI of 141.5 KWh/m^2/yr, established by a 2015 national survey of existing residential building stock (MEDENER, 2017). This could be primarily attributed to the building envelope (walls, roof, and glazing). The low insulation values in external walls, floor, and roof were a major driver of energy consumption in the building. Similarly, the low performance windows also attributed to significant heat gains and losses through the building envelope. Cooling and heating loads combined accounted for 33% of the total energy demand in the building, followed by equipment at 26%, and lighting at 24%. This is indicative of a thermally low-performing building envelope and HVAC system. Heating loads were highest between December and March, while cooling loads were highest between June and September. Lighting loads were considerable year-round due to the low window to wall ratio of the building envelope, hence, requiring more electrical supply. The peak energy consumption occurred between July and August due to the heavy reliance on air conditioning to combat the summer heat and humidity. Nonetheless, equipment and plug loads were the single highest energy consuming end-users due to the proliferation of various plugin electrical appliances, resulting in a significant hike in cooling loads. The low-insulative thermal mass properties of the building envelope (walls, roof, windows) and low-performance HVAC systems were major drivers of energy loads, and therefore require serious attention to conserve and minimize energy consumption. The baseline simulation results clearly show an urgent need to increase the envelope's overall insulation values as well as HVAC systems.

Conclusion

The baseline modeling and simulation results were in line with current metrics and data in the Lebanese residential multifamily market. The residential housing sector is one of the largest consumers of energy in the nation and hence present a unique opportunity to affect real and measurable change in the country's energy outlook. Nonetheless, lack of robust green construction practices and applications within the residential industry remains a significant hurdle towards improving and propagating energy efficiency and conservation measures. As such, energy consumption patterns in Lebanese multi-family apartment blocks remain unattainable and excessive, exceeding many regional counterparts. Space conditioning needs constituted the highest energy end-use among all other variables, dominated by heating and cooling loads. Hence, efforts should focus on minimizing these loads by optimizing design configurations, improving system/equipment efficiencies, and increasing insulation values of building envelopes. The research aims to use this parametric and iterative energy modeling approach to provide an optimal benchmark for energy consumption in standard Lebanese apartment blocks. The base model also provided an energy performance benchmark to formulate more effective and robust energy conservation measures within the residential building industry. It's imperative to have better and more robust data to effectively change construction paradigms in the country. Lastly, the simulated model was intended to serve as a foundational baseline towards the goal of achieving Net Zero Energy multi-family residential buildings in Lebanon.

Chapter 6: Expected Outcomes, Research Deliverables & Implications

Anticipated Research Results

The research aims to provide all-inclusive optimal guidelines for the design of high-performance Net Zero Energy standard apartment buildings in Lebanon. The research intends to generate information that will help in minimizing the impact of the residential sector on energy consumption and associated air pollution. The objective of the research is to promote the adoption of high-performance apartment buildings that cost less to operate, are thermally comfortable, and have a positive influence on the overall environment. The research generated a comprehensive set of performance-based guidelines for Net Zero Energy residential apartment buildings. The following outcomes will be recommended based on the research findings:

- A targeted list of architectural indicators encompassing the most optimal combinations of building **Design** and building **Systems** variables, including both **Passive** & **Active** strategies.
- All-inclusive optimal architectural guidelines for the design of high-performance Net Zero Energy apartment buildings.

I expect a set of top energy-performance indicators will emerge after completing the parametric energy modeling simulations of the various permutations of architectural variables. key figures will display the impact of these high-performance indicators against the building's energy use intensity and overall annual energy consumption. It is likely that certain combinations of building system upgrades might yield higher returns than others. For example, an efficient HVAC system with thermally insulated envelope should yield high returns as it directly impacts overall energy consumption patterns. Similarly, a compact footprint with a low percentage of southern window to wall ratio is expected to impact energy use positively. I anticipated the following variables to constitute the most optimal high-performance energy indicators:

- Architectural design indicators: (1) compact footprint, (2) south-facing shading systems, and (3) low percentage southern window to wall ratio (WWR).
- Architectural system indicators: (1) super insulated envelope, (2) high efficiency HVAC system, (3) high-performance glazing, and (4) high efficiency lighting.
- Accordingly, the most optimal combination of architectural indicators is expected to include a super-insulated envelope, high efficiency HVAC system, high performance glazing, high efficiency lighting and equipment, compact footprint, and south-facing shading systems.

These specific architectural indicators were forecasted to heavily influence the simulated outcomes of the energy modeling runs. As such, these variables would be designated as "optimal energy-performance indicators," to be considered as a foundational basis for industry best practices guidelines. Thereafter, these top performing indictors will hopefully form a new baseline threshold for energy use in standard Lebanese apartment buildings. Furthermore, research findings are expected to drive the residential industry toward more sustainable building practices and approaches, and in turn, inform policy makers, building professionals, and homeowners on better and more robust ways to approach energy conservation measures in residential buildings. It is the aim of this research to contribute and add to the existing body of literature to advance the residential energy market towards a more sustainable paradigm and a more resilient future.

Key Research Deliverables

The fundamental premise of the research was to affect transformative change from the bottom up to help the Lebanese people. The research aimed to generate a body of knowledge that will assist in proliferating the efforts to minimize the impact of the residential sector on energy use and associated air pollution, as well as amplify the adoption of energy conservation measures in the Lebanese residential building sector. The objective of the research was to promote the adoption of high-performance apartment buildings that cost less to heat and cool, are more comfortable and healthier for occupants, and have a positive impact on the environment. It was the aim of this research project to cause a paradigm shift within the Lebanese residential sector and building sector at large to yield resiliency from political crises, provide economic independence, promote social equity and safety, and most importantly reduce energy poverty and inequity. The primary objectives of the research were:

- Developing and promoting alternative solutions to residential building practices in Lebanon that Provide healthier indoor environments, comfortable indoor conditions, and reduces energy use & waste
- Developing a robust design framework for residential NZEB in Lebanon that will alleviate economic concerns, reduce energy poverty, as well as promote social equity.

- Raising public awareness as it relates to energy use and energy conservation measures in Lebanese residential buildings utilizing workshops, lectures, and publications.
- And lastly, achieving resiliency, independence, autonomy, and safety, environmentally, economically, and socially.

The following table outlines the main methodologies, objectives, and deliverables of the proposed research.

Table 7. Objectives, methodologies, and deliverables for each stage of the research

Research Stage	**Background Analysis**	**Perception Analysis**	**Baseline Modeling Analysis**	**Parametric Modeling Analysis**
Objective	To identify energy consumption patterns and explore existing gaps.	To explore end-users' perceptions of ZEHs and energy efficiency, as well as knowledge and intertest of ZEHs.	To establish a reference base scenario and set benchmarks for energy use in a standard apartment building.	To explore via simulations the impact of various architectural variables and upgrades on energy use in a standard apartment building.
Methodology	Literature research.	Research Surveys administered to US and Lebanese populations.	Architectural modeling platforms such as Sketchup and Designbuilder.	Energy simulation platforms and plugins such as Sefaira and the Cove Tool.
Deliverable		Recommendations and guidelines to address barriers and knowledge gaps to increase awareness and positive perception of Zero Energy Homes.		Develop comprehensive performance-based guidelines for NZE apartment buildings. Develop framework for an informational mobile App.

Crises, Impacts, and Implications

Lebanon has experienced a tumultuous history, riddled with crises and conflicts. The country is experiencing 3-prong calamities right now, a persistent political crisis, a severe economic collapse, and wide-spread social unrest (Figure 119). A caretaker resigned government has been in place since 2020 with no end in sight for the formation of an effective government. The political deadlock has affected all sectors of society and completely crippled the already broken nation. Moreover, the current pandemic further exacerbated the already fragile existing socio-economic situation. The country's economy completely collapsed under the weight of the dueling political and health crises. Social unrest has become prevalent and widespread across all sectors of the population, but especially among the middle- and low-income populations.

Figure 119. Images showing the multiple crises in Lebanon (courtesy of Google images)

In 2021, the World Bank, in its annual forecast, rated Lebanon's crisis among the world's worst since the 1850s. To that end, people in Lebanon have no access to reliable power supply most hours of the day. The country has been experiencing severe chronic power outages, resulting in electrical coverage for few hours of the day. Energy poverty is now a prevalent occurrence afflicting wide swaths of the population. To further exacerbate matters, Lebanon has been suffering from a serious gas shortage causing hour-long waits in lines for fuel (Figure 120). This has also affected the private electrical power supply system people rely on to augment and fill the void caused by the lack of coverage by public power utilities. The gas shortage problem is so severe even private generator operators have run out of diesel supply. As a result, Lebanese households and business have found themselves at the mercy of gas mafias and the whims of political operatives. In Aggregate, the confluence of the political, social, health, and economic crises has resulted in massive inflation unseen since the civil war. To that end, Lebanon surpassed Zimbabwe and Venezuela for the most hyperinflation in the world in 2021.

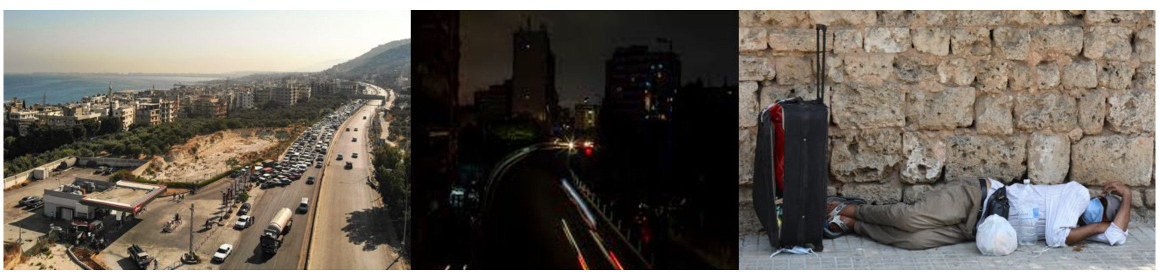

Figure 120. Images depicting the gas shortage and social crises in Lebanon (courtesy of Google images)

The political, economic, social, and health crises have placed Lebanon on the brink of total collapse. The country's social safety nets have been obliterated. People are struggling to cope with unhuman living conditions. Grocery stores are running out of food, gas stations are operating on a very limited basis, power supply is intermittent at best, crime rate have risen considerably over the past year, but most critically, people have lost hope and faith (Figure 121). Moreover, people don't have free access to their own money due to withdrawals limits imposed by banks to prevent total financial market collapse.

Figure 121. Images showing the daily troubles of Lebanese people (courtesy of Google images)

These mounting and escalating crises has affected all sectors of society. However, the middle to low-income population has been the hardest hit (Figure 122). Alternatively, the rich and powerful have been immune from these crises and on the contrary, many have benefited from them. This has created a massive divide across the various segments of the population leading to social turbulence and instability. Furthermore, the caretaker government and political class has completely abdicated their duties and responsibilities. The people of Lebanon feel abandoned and neglected, and many have chosen to leave the country when given a chance. As a result, Lebanon is experiencing a massive outward migration movement of people, especially young and educated, creating a significant and dangerous vacuum in the existing social order and societal construct.

Figure 122. Images depicting the daily struggles of Lebanese citizens (courtesy of Google images)

To make matters worse, Lebanese currency has been severely devalued due to hyperinflation to the point that it has lost all monetary value. For example, the one US dollar exchange rate of 1500 Lebanese pounds from 2019 is now up to approximately 30,000* Lebanese Liras/pounds (*when the report was written, 2021-2022*). On average, a Lebanese makes around 2,280,000 LBP per month, equivalent to $75 in today's market (January 13, 2022) compared to $1500 a year ago. As a result, people are struggling to make ends meet given that the average utility cost per month is around $100 and average apartment rent per month around $850. Lebanon's per capita income dropped by 69 % from $8,000 in 2018 to $2,500 in 2020. The average monthly salary plummet by 84 percent, down from $900 in 2018 to less than $100 in 2021-22. All added, Lebanese are struggling to survive. A United Nation's ESCWA 2021 policy brief reported that 4 million residents of Lebanon (82% of population) suffer from multidimensional poverty, defined as the inability to access health care, electricity, or housing. A staggering three quarters of Lebanon's population is now below the poverty line. The minimum wage now sits at an equivalent of $1.17 per day, among the lowest in the world. Lebanese citizens and households are facing an unknown future punctuated by political turmoil, financial ruins, social inequity, and an ongoing health crisis.

Lebanon's faces extreme challenges on many fronts, including the threats from climate change and its associated impacts. The country's problems are forecasted to rise with climate change as it will affect various aspects of life in Lebanon, including healthcare, water availability, energy demand, and natural resources. It's projected inevitable rising temperatures will severely deplete water sources in a country that already struggles with water scarcity and availability. To that end, the UN's UNICEF organization issued a dire warning in August 2021 that 4 million Lebanese citizens face the risk of being cut off from a safe water supply if conditions persisted as is. A wide swath of the population is in danger of losing critical access to clean potable water. Moreover, water scarcity will also have an impact on agricultural and farming practice s in Lebanon, a sector already suffering from the mounting crises of fuel, electricity, and currency devaluation. The climbing temperatures, associated with climate change, will also increase energy demand to meet the ever-rising cooling demands, which the existing electrical infrastructure can't meet currently. It's projected that massive additional stress will be added onto the aging and inadequate existing power grid leading to chronic and widespread power outages and blackouts. Moreover, Lebanon has seen a rise in heat waves during the summer, further exacerbated by ongoing power outages leading to serious public health concerns. This will affect household's bottom-line and have grave implications environmentally, socially, and economically. Furthermore, these crises have impacted the well-being, health, and quality of life of large segments of the population, specifically middle to low-income socio-economic sectors. The fundamental Premise of the research was providing Lebanese people a path towards resiliency and immunity from potential future crises, specifically as it relates to their homes and households. The main objective of this research was to develop alternative solutions to residential building practices in Lebanon that would provide healthier indoor environments, comfortable indoor conditions, as well as reduce energy consumption and waste. To that end, the research aimed to develop a robust design framework for residential Net Zero Energy Buildings in Lebanon to alleviate economic burdens, reduce energy poverty, and promote social equity. It's imperative to raise public awareness as it relates to energy use and energy conservation measures to effectively cause a paradigm shift in behavior and approach. To that end, the objective was to affect transformative change from the bottom up to help the Lebanese people rebuild their lives in a more sustainable and resilient manner. Net Zero Energy homes are an integral piece of this very complex puzzle that could promote resilience from future inevitable political crises and their impacts across society. They also provide a sense of economic independence allowing people to save more money as well as reduce societal energy poverty. But most importantly, Net Zero Energy homes would promote a sense of safety, security, and social equity amongst the most afflicted sectors of the Lebanese society. Moreover, and given the state of energy and electricity production in Lebanon coupled with unhealthy and uncomfortable indoor environments, a Net Zero Energy approach offers households resiliency, independence, and autonomy. A Net Zero Energy path would significantly lessen the financial burden of Lebanese households. Zero Energy Homes offer a robust path towards achieving environmental justice, social equity, and economic stability. The main objective of this research was to promote sustainability, resiliency, independence, and safety on three levels, environmentally, economically, and socially.

Research Limitations

The research aimed to develop comprehensive guidelines for residential building practices in the context of zero energy homes in Lebanon. The thesis was developed under the assumption that ample time would be available to conduct a comprehensive analysis of diverse variables encompassing architectural metrics in a standard Lebanese residential apartment building. This proved to be somewhat difficult due to the immense number of permutations possible from such an endeavor. To address that issue, a detailed targeted list of optimal iterations and permutations was developed and established, based on research and current best practices, to set an achievable project.

The robustness and efficacy of energy simulation tools was another limitation to this project. The accuracy and predictability of such tools have not yet reached a high degree of confidence. Furthermore, a recent study explored the "energy performance gap — the difference between promised energy savings in green buildings and the actual savings delivered" (Cali, 2016). The author concluded that this gap was due to inept energy modeling tools that fail to accurately depict how buildings really work under certain conditions. Furthermore, the building occupants' behavior was also a significant trigger for the energy performance gap. To circumvent these potential issues, the study employed various robust energy modeling tools to normalize the findings across various platforms. Results were then compared and analyzed to generate reasonable and accurate data. Another area of limitation was the ability to exchange and extrapolate data seamlessly between 3-D modeling environments and energy modeling and simulation platforms. To that end, modeling tools were selected based on their interoperability and ability to exchange and share data across their respective simulation platforms (NREL, 2011). The Cove Tool was selected as the primary simulation engine due to its efficacy and robustness. However, the platform didn't represent accurately contextual costs and LCA data. Hence, cost parameters and analysis were not included in the scope of the research. Lastly, access to reliable consistent data was and remain problematic and difficult since Lebanon is a chronically plagued with corruption and an archaic hierarchal bureaucracy. The country lacks established performance benchmarks and baselines. Moreover, it's quite difficult to attain accurate and consistent data sets, especially as it relates to residential construction practices and energy consumption patterns. Hence, it’s the aim of this research to establish a foundational base of knowledge from which more research can be initiated.

Chapter 7: Parametric Modeling and Simulation Analysis

Parametric Design Modeling Iterations and Options

Parametric modeling analysis and simulation was initiated after baseline parameters and benchmarks were established via the Cove Tool building performance modeling platform, utilizing the reference modeled apartment building as a starting point. The parametric modeling analysis targeted and explored various diverse sets of architectural design variables to assess their impact on energy consumption and building performance. The modeling and simulation analysis examined the correlation between various design variables and overall energy consumption via the energy use intensity (EUI) performance metric. To that end, baseline design parameters were modified, modeled, and simulated one variable at a time to effectually assess the implication of specific interventions on energy demand in a multi-family apartment building. Each parametric design simulation run involved a set of dependent and independent variables. Energy use intensity was deemed the dependent variable, while architectural design parameters instituted the independent variables. Design simulation scenarios encompassed the following architectural variables: building massing (footprint and layout), roof characteristic (shape & style), shading systems (louvers, solar screens), façade design, and window to wall area ratios (WWR). All design strategies were based on literature review case study research of buildings in similar climates and Lebanon specifically. Moreover, these strategies were adopted based on contextual research of standard Lebanese apartment buildings.

Parametric Design Modeling Runs: Building Massing/Footprint (passive Strategy)

The first set of parametric design scenarios explored the impact of building massing footprint variations on energy consumption in a typical multi-family apartment building. The modeling and simulation analysis compared various geometric footprint iterations against the baseline scenario (compact square footprint at 20m x 20m). All baseline assumptions, including building volume, overall size, construction specifications, number of floors, and design parameters, were maintained except for the building footprint. The modeling and simulation runs targeted solely the impact of footprint modifications on energy consumption and overall EUI. The parametric runs sought to examine the connection between building footprint variation and energy use intensity to assess the efficacy of such an intervention. The following massing footprint design iterations were modeled and evaluated using the Cove Tool energy simulation platform (Figure 123): massing footprint #1 (Courtyard option), massing footprint #2 (U-shape option), massing footprint #3 (H-shape option), and massing footprint #4 (rectangular option).

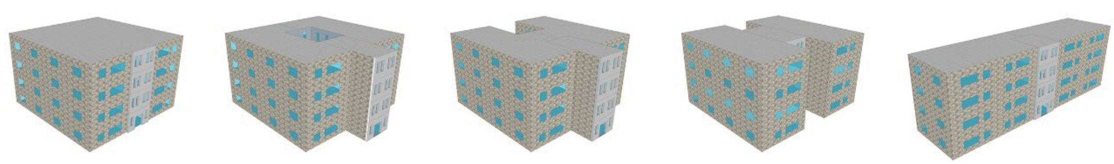

Figure 123. Diagram showing the various massing footprint iterations

Parametric Design Modeling Runs: Building Roof (passive Strategy)

The second set of parametric design scenarios explored the impact of building roof variations on energy consumption in a typical multi-family apartment building. The design iterations focused on roof shapes and styles, compared against the baseline scenario of a flat roof condition. All baseline assumptions were maintained except for the roof shape. The modeling and simulation runs exclusively assessed the impact of roof design modifications on energy consumption to measure the effectiveness of such a change. Three sets of roof design parameters were modeled and evaluated, encompassing a gable-roof, a hip roof, and a mansard roof (Figure 124).

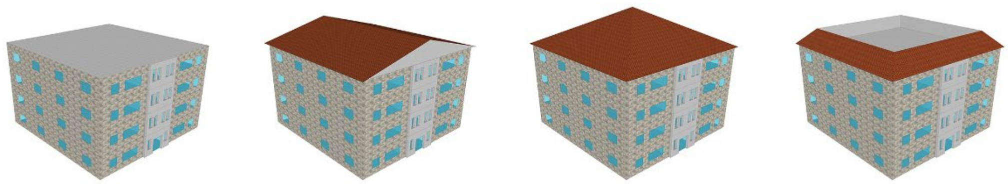

Figure 124. Diagram showing the various roof iterations

Parametric Design Modeling Runs: Shading Systems (passive Strategy)

The next set of parametric design options explored the impact of incorporating shading systems on energy consumption. The simulations kept all baseline parameters intact and evaluated the impacts of adding shading devices to certain facades of the buildings. A diverse set of options were assessed including integrating shading devices on the south façade, on south-west-east facades, on west-east facades, and a south-facing solar screen system (Figure 125).

Figure 125. Diagram showing the various shading iterations

Parametric Design Modeling Runs: Façade Design (passive Strategy)

Façade design iterations were also investigated to evaluate the efficacy of such design options on overall energy consumption in the building. The parametric simulations maintained all baseline conditions except for façade design parameters. The analysis encompassed window redesign iterations, floor plate variations, and covered balcony additions. The façade design variations examined the impact of changing window orientation and layout on energy consumption in the building. To that end, façade design modeling iterations included the following options: addition of balconies on all facades, façades push and pull, east-west façade window re-design, and north-south façade window re-design (Figure 126).

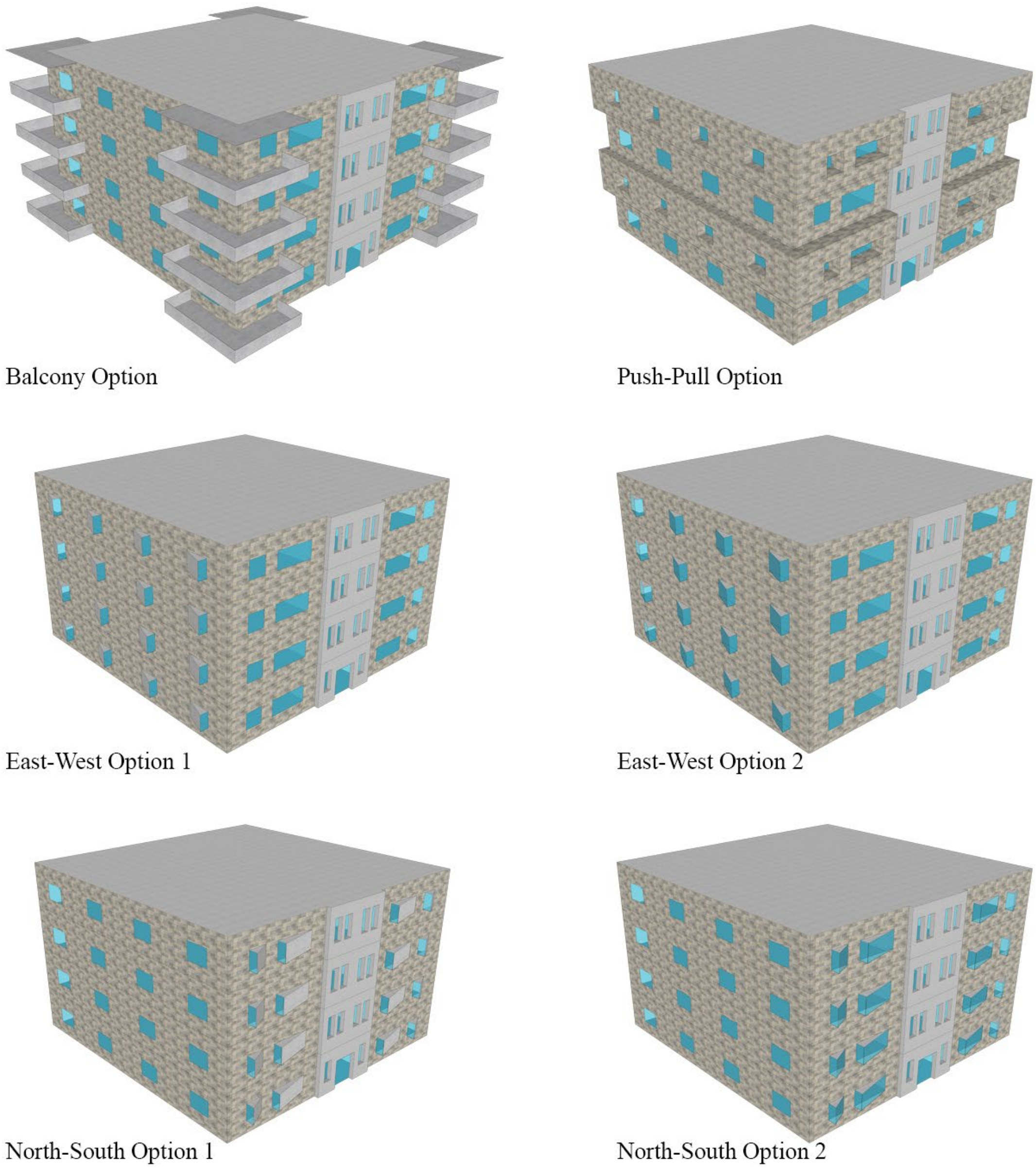

Figure 126. Diagrams showing variations of facade re-design

Parametric Design Modeling Runs: Window to Wall Area Ratios (passive Strategy)

The last set of design options investigated encompassed window to wall area ratio iterations (WWR). Window area was defined as a percentage of each façade's exterior wall area. WWR percentage variations were than modeled to evaluate their impact on energy consumption in the building, while keeping all other baseline parameters constant. The design options examined various WWR percentages assigned to the North (N)%, South (S%), East (E%), and West (W%) facades. The primary focus of the investigation targeted window area modifications on the southern and northern facades of the building. The following WWR iterations were modeled and simulated: V1_N25%-E22%-S22%-W22% (V1), V2_N25%-E11%-S11%-W11% (V2), V3_N12%-E11%-S11%-W11 (V3), V4_N0%-E11%-S11%-W11 (V4), V5_N0%-E0%-S11%-W11% (V5).

Parametric System Modeling Iterations and Options

The next set of parametric modeling analysis and simulation encompassed a methodical examination of various building systems upgrades, to evaluate their impact on energy consumption and building performance. The modeling and simulation analysis examined the relationship between various building system variables and overall energy consumption utilizing energy use intensity (EUI) as a performance metric. Baseline design parameters were modified, modeled, and simulated one variable at a time to effectively measure the impacts of targeted changes on energy demand in a multi-family apartment building. Each parametric design simulation run involved a set of dependent and independent variables. Energy use intensity was deemed the dependent variable, while building systems upgrades were the independent variables. Building system upgrades encompassed the following variables: building envelope specifications, HVAC systems, domestic hot water systems, glazing systems, lighting equipment, and space conditioning schedules.

Parametric System Modeling Runs: Building Envelope (passive Strategy)

The first set of parametric building systems scenarios examined the impact of envelope specification variations on energy consumption in a typical multi-family apartment building. The Cove Tool building performance platform was used to assess the relationship between building envelope variations and energy consumption. The modeling and simulation analysis specifically assessed the correlation between building envelope upgrades and overall performance, using R-values and U-values as the primary independent variables measured against overall building energy use. The parametric runs sought to examine the connection between building envelope upgrades and energy use intensity, to assess the effectiveness of such an intervention. All other initial baseline assumptions were kept. The evaluation and simulation analysis encompassed the following building envelope variables: exterior wall construction and insulation, roof insulation, floor slab insulation, external wall emissivity, and envelope heat capacity (Table X).

Table 8. Building envelope specifications and characteristics

Category	Specifications
Envelope Construction	U Values (W/m² K)
85 PCF **8" CMU** block wall with polyurethane foamed in-place insulation 4" un-insulated concrete roof 6" un-insulated concrete floor slab	Wall= 0.117 Roof = 0.32 Floor= 0.48 Below grade= 2.5
85 PCF **10" CMU** block wall with polyurethane foamed in-place insulation 4" un-insulated concrete roof 6" un-insulated concrete floor slab	Wall= 0.095 Roof = 0.32 Floor= 0.48 Below grade= 2.5
85 PCF **12" CMU** block wall with polyurethane foamed in-place insulation 4" un-insulated concrete roof 6" un-insulated concrete floor slab	Wall= 0.077 Roof = 0.32 Floor= 0.48 Below grade= 2.5

85 PCF **14” CMU** block wall with polyurethane foamed in-place insulation 4” un-insulated concrete roof 6” un-insulated concrete floor slab	Wall= 0.065 Roof = 0.32 Floor= 0.48 Below grade= 2.5
85 PCF **16” CMU** block wall with polyurethane foamed in-place insulation 4” un-insulated concrete roof 6” un-insulated concrete floor slab	Wall= 0.056 Roof = 0.32 Floor= 0.48 Below grade= 2.5
85 PCF **6”, 8”, 10”, 12” Double CMU** cavity wall with 3.5” polyiso insulation and masonry veneer 4” un-insulated concrete roof 6” un-insulated concrete floor slab	Wall= 0.032 Roof = 0.32 Floor= 0.48 Below grade= 2.5

Parametric System Modeling Runs: HVAC Systems (active Strategy)

Space cooling and heating conditioning account for around 50% of typical household energy consumption (DOE, 2017). High performance heating, ventilation, and air conditioning systems (HVAC) are instrumental in providing optimal energy performance. The next set of parametric modeling runs examined the impact of HVAC system variations on energy consumption in a typical multi-family apartment building. All other baseline assumptions were maintained as modeled. The energy modeling runs sought to assess the impact of HVAC system variations on energy consumption. The simulations encompassed variations of the following HVAC systems: ground source heat pumps (GSHP) and air source heat pumps (ASHP) (Table 9).

Table 9. HVAC system specifications and characteristics

Category	Specifications
HVAC System	**COP**
V1-GSHP with dedicated outside air system (DOAS) with fan coil unit (FCU)	Heating COP: 3.7 Cooling COP: 5.2 Infiltration: 1.15 $m^3/h/m^2$
V2-GSHP with Direct Outside Air System (DOAS) with Induction	Heating COP: 3.7 Cooling COP: 5.2 Infiltration: 1.15 $m^3/h/m^2$

V3-GSHP with dedicated outside air system (DOAS) with Radiant	Heating COP: 3.7 Cooling COP: 5.2 Infiltration: 1.15 $m^3/h/m^2$
V4-GSHP with Variable Air Volume System (VAV) with Reheat	Heating COP: 3.7 Cooling COP: 5.2 Infiltration: 1.15 $m^3/h/m^2$
V5-GSHP with Constant Air Volume System (VAV) with Reheat	Heating COP: 3.7 Cooling COP: 5.2 Infiltration: 1.15 $m^3/h/m^2$
V6-ASHP with dedicated outside air system (DOAS) with fan coil unit (FCU) and Air-Cooled Chiller	Heating COP: 2.05 Cooling COP: 3.75 Infiltration: 1.15 $m^3/h/m^2$
V7-ASHP dedicated outside air system (DOAS) with fan coil unit (FCU) and Water-Cooled Chiller	Heating COP: 2.05 Cooling COP: 4.3 Infiltration: 1.15 $m^3/h/m^2$
V8-ASHP with Variable Air Volume System (VAV) with Reheat and Water-Cooled Chiller	Heating COP: 2.05 Cooling COP: 4.25 Infiltration: 1.15 $m^3/h/m^2$
V9-ASHP with Constant Air Volume System (VAV) with Reheat and Water-Cooled Chiller	Heating COP: 2.05 Cooling COP: 4.3 Infiltration: 1.15 $m^3/h/m^2$

Parametric System Modeling Runs: DHW Systems (active Strategy)

The next set of systems encompassed an analysis of domestic hot water systems (DHW). The energy modeling runs evaluated the impact of domestic hot water system variations on energy performance and consumption, specifically heat pump water heating systems. To determine the effectiveness of such a change, the parametric runs examined the association between hot water system specifications and energy use intensity. All other baseline modeling assumptions were kept as modeled. The modeling investigation encompassed the following variables: domestic hot water typology, distribution system, and overall demand.

Parametric System Modeling Runs: Glazing Systems (passive Strategy)

Window systems are considered one of the weakest components within a building's overall thermal envelope. The next set of energy modeling runs examined the impact of glazing specification variations on energy use in a multi-family apartment building. The simulations assessed the connection between window-typology properties and overall energy performance. The modeling variations encompassed the following glazing categories: Thermal transmittance (U-value), number of window panes, emissivity (Low-E), visible transmittance (Tvis), and solar heat gain coefficient (SHGC) (Table 10). All other assumptions were retained from the baseline model. The parametric runs sought to examine the relationship between building glazing variations and energy use intensity.

Table 10. Glazing system specifications and characteristics

Category	Specifications
Glazing Systems	
V1-Double pane, clear glass with 1/4" air space	U-Value: 0.59 W/m^2 K SHGC: 0.25 Tvis: 81%
V2-Double pane, clear glass with 1/2" air space	U-Value: 0.49 W/m^2 K SHGC: 0.25 Tvis: 81%
V3-Double pane, clear glass with 3/4" air space	U-Value: 0.42 W/m^2 K SHGC: 0.25 Tvis: 81%
V4-Triple pane, clear glass with 1/4" air space	U-Value: 0.39 W/m^2 K SHGC: 0.25 Tvis: 74%
V5-Triple pane, clear glass with 1/2" air space	U-Value: 0.30 W/m^2 K SHGC: 0.25 Tvis: 74%
V6-Double pane with one Low-E coating and Argon Gas	U-Value: 0.26 W/m^2 K SHGC: 0.25 Tvis: 79%
V7-Triple pane with one Low-E coating and Argon Gas	U-Value: 0.18 W/m^2 K SHGC: 0.25 Tvis: 73%
V8-Triple pane with two Low-E coatings and Argon Gas	U-Value: 0.13 W/m^2 K SHGC: 0.25

	Tvis: 70%

Parametric System Modeling Runs: Lighting Systems (active Strategy)

Lighting upgrades were modeled next to evaluate the effect of such an intervention on overall energy performance. The energy simulation runs exclusively examined the relationship between lighting system upgrades and energy use intensity. All other assumptions were retained from the baseline condition. The following lighting parameters were investigated: LED fixtures, daylight sensors, occupancy sensors, and lighting power density (LPD).

Parametric System Modeling Runs: Space Conditioning Schedules (active Strategy)

The last set of parametric runs evaluated the impact of space-conditioning schedules variations on overall energy consumption. The energy modeling runs specifically tested the connection between heating and cooling conditioning set-point and set-back variations and energy use intensity, to evaluate the effectiveness of such an intervention. All other baseline assumptions were kept as modeled initially. The simulation analysis assessed the following measures: cooling set points and setbacks and heating set points and setbacks (Table 11).

Table 11. HVAC scheduling system specifications

Category	Specifications
Space Conditioning Schedule	
Heating Set-Point	20 C (68 F)
Heating Set-Back	15 C (59 F)
Cooling Set-Point	25 C (77 F)
Cooling Set-Back	29 C (84 F)

Chapter 8: Parametric Modeling and Simulation Results

Parametric Design Modeling Results

Parametric energy modeling analysis and simulation results were generated using the Cove Tool building performance platform. The results were based on a parametric singular design variable evaluation. The findings encompassed energy performance data for the following design options: building massing, building roof, shading systems, façade design, and window to wall ratios. Whole building Energy Use Intensity (EUI) was employed as the main performance metric to compare and assess the various simulated parametric design iterations.

Building Massing/Footprint Iteration Results

The first set of parametric design modeling scenarios explored the impact of building massing footprint variations on energy consumption in a typical multi-family apartment building. The modeling and simulation analysis compared various geometric footprint iterations (Courtyard option, U-shape option, H-shape option, and rectangular option) against the baseline scenario (compact square-shaped footprint at 20m x 20m). All massing options retained the same square footage area size. None of the modeled massing and footprint options yielded simulation results below the baseline energy consumption benchmark. On the contrary, all modeled iterations consumed more energy than the baseline model. The compact square-shaped footprint option remained the most optimal massing form in terms of overall performance and corresponding energy breakdown consumption (Figure 127).

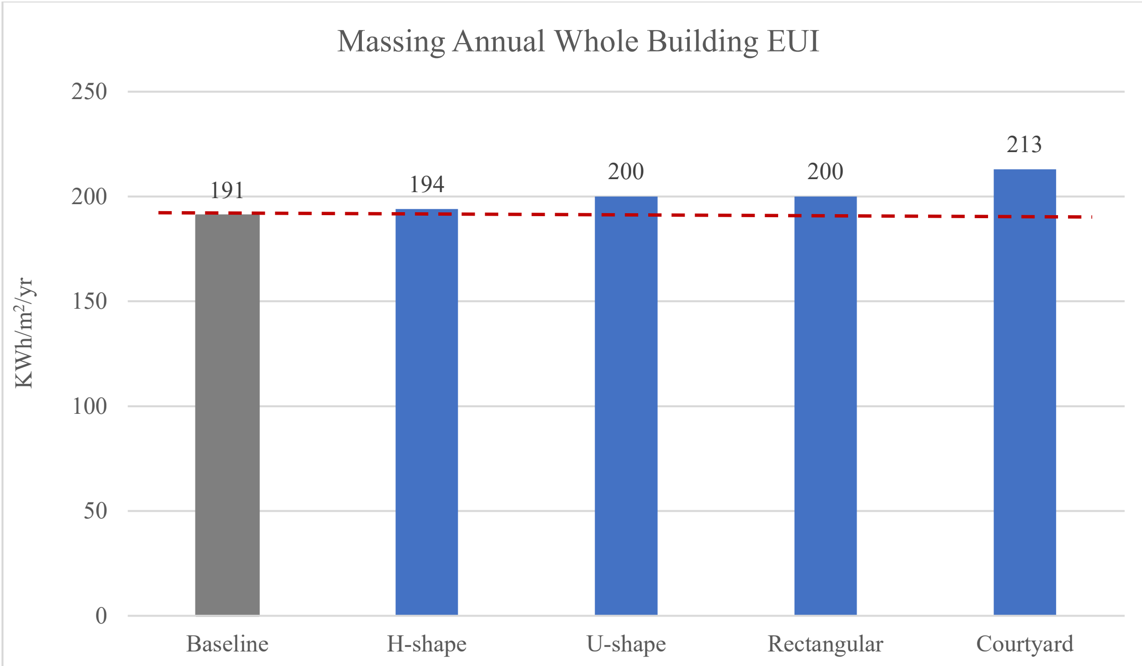

Figure 127. EUI results for parametric footprint/massing iterations.

Building Roof Iteration Results

The next set of parametric design modeling iterations explored the impact of building roof variations on energy consumption. Three sets of roof design parameters were modeled and evaluated against the baseline scenario of a flat roof condition, including a gable-roof, a hip roof, and a mansard roof. Building volume and overall gross area remained the same as the baseline model and across all parametric simulated iterations. Simulation results show the flat roof condition as the most optimal iteration in terms of overall energy consumption (Figure 128). To that end, the hip roof option performed similarly to the baseline condition, while the gable roof iteration consumed slightly more energy (0.5%). On the other hand, the mansard roof option consumed approximately 10% more energy than the baseline condition.

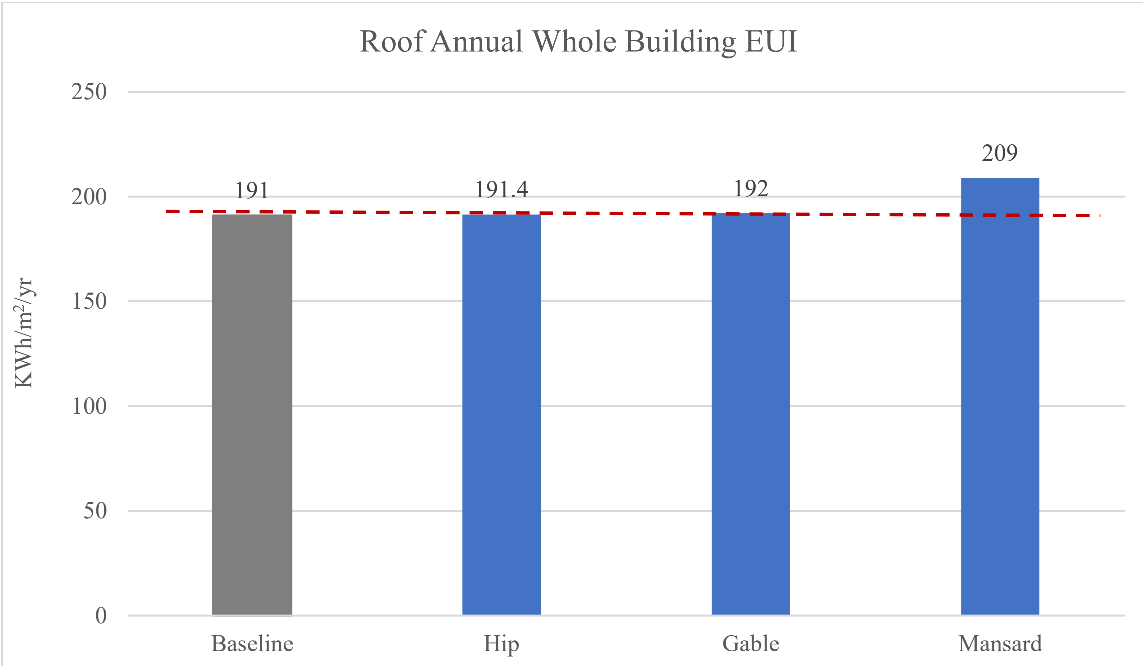

Figure 128. EUI results for parametric roof iterations.

Shading Systems Iteration Results

The next set design variables examined the impact of integrating shading systems into the building façade on energy consumption and performance. A series of options were evaluated including incorporating horizontal shading devices on the south façade only (S), horizontal shading devices on the south façade with vertical devices on the west and east facades (SWE-V1), horizontal shading devices on the south façade coupled with both vertical and horizontal devices on the west and east facades (SWE-V2), horizontal shading devices on the west and east facades (WE), and a full south-facing vertical solar screen system. Most simulated shading iterations yielded similar energy performance results as the baseline condition with no shading systems (Figure 129). Nonetheless, incorporating horizontal shading devices on the south façade coupled with vertical and horizontal devices on the west and east facades (SWE-V2) yielded a marginal 0.5% reduction in overall energy consumption.

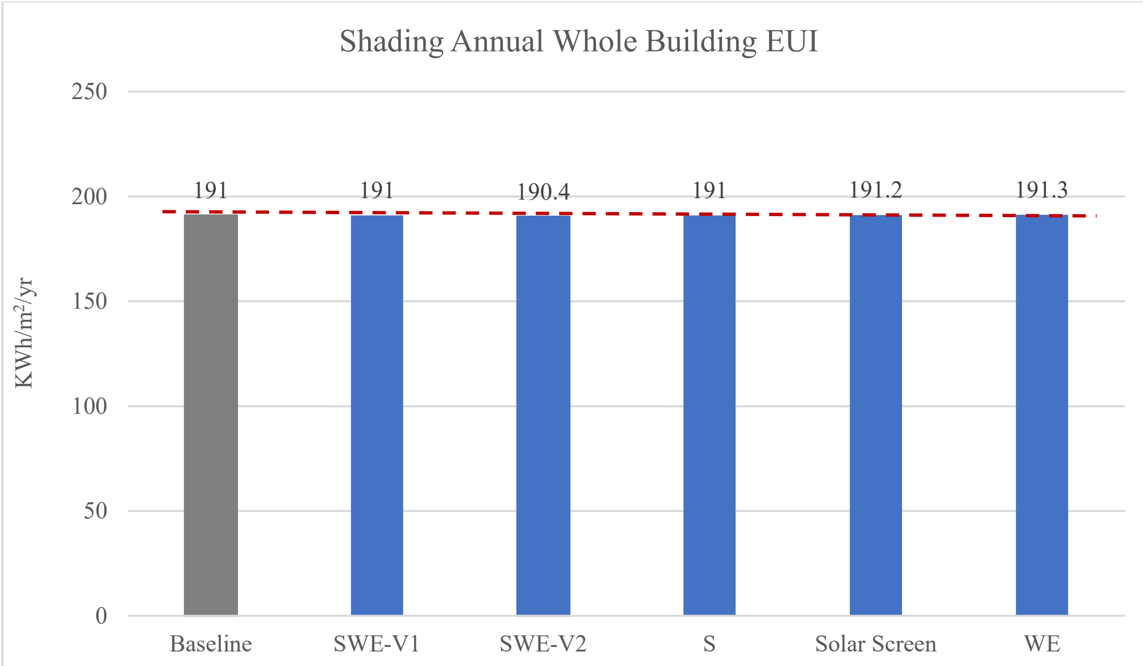

Figure 129. EUI results for parametric shading system iterations.

Façade Design Iteration Results

The next set of parametric design modeling iterations explored the impact of façade design variations on energy consumption. The following options were evaluated: addition of balconies on all facades, façades push and pull, two versions of east-west façade window re-design (EW-V1_V2), and two versions of north-south façade window re-design (NS-V1_V2). The balcony façade option yielded similar performance values as the baseline condition. On the other hand, the push-pull, east-west (EW-V2) and north-south (NS-V2) façade redesign options 2 generated slightly higher energy use than the baseline condition. The only façade design iterations to consume less energy than the baseline, albeit marginal, were the north-south (NS-V1) and east-west (EW-V1) façade options 1. To that end, they reduced energy consumption by 1.7% and 0.3 % respectively, compared to the baseline design model (Figure 130).

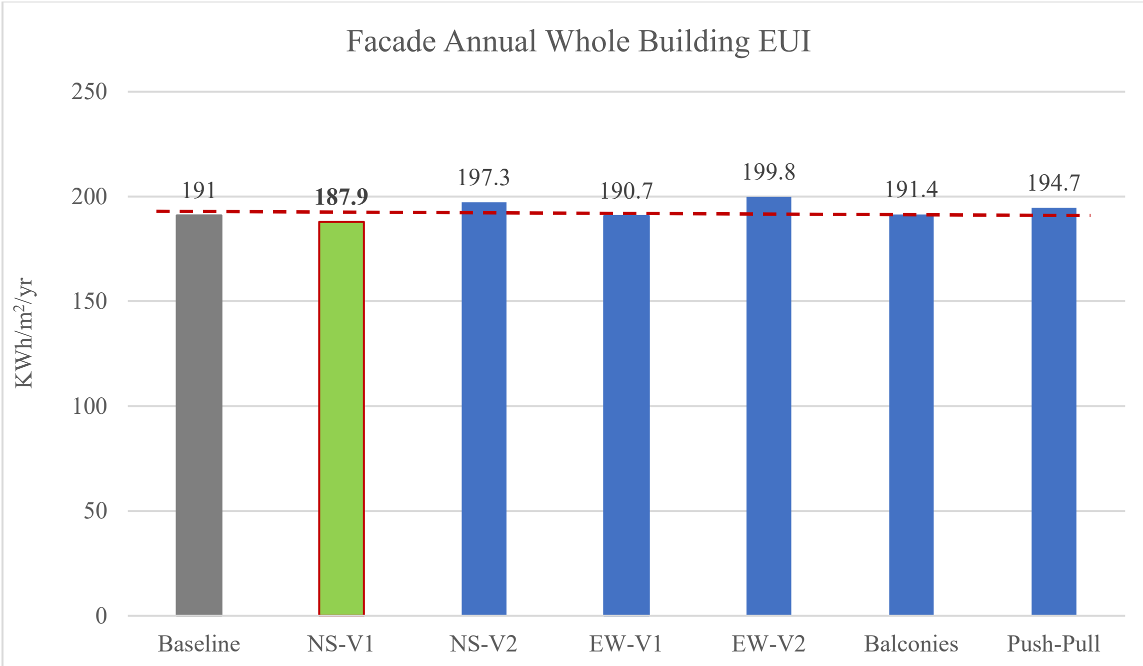

Figure 130. EUI results for parametric façade design iterations.

Window to Wall Ratio Design Iteration Results

The last set of design options examined the effect of window to wall area ratio (WWR) variations on energy use in a multi-family apartment building. All other modeled baseline parameters remained the same. The following WWR iterations were modeled and simulated: Version 1_N25%-E22%-S22%-W22% (V1), Version 2_N25%-E11%-S11%-W11% (V2), Version 3_N12%-E11%-S11%-W11 (V3), Version 4_N0%-E11%-S11%-W11 (V4), Version 5_N0%-E0%-S11%-W11% (V5). Versions 1 and 2 yielded higher energy use than the baseline condition at 7% and 1% respectively. However, simulation results revealed energy reductions amongst versions 3, 4, and 5, yielding 2%, 4%, and 6.5% energy consumption decreases respectively when compared to the baseline model. The largest energy reduction was generated by version 5 that had window placements exclusively on the south and west facades at an 11% window to wall ratio (Figure 131).

Energy consumption reductions were mostly realized via heating end-use, generating a 22% reduction from the baseline with version 5.

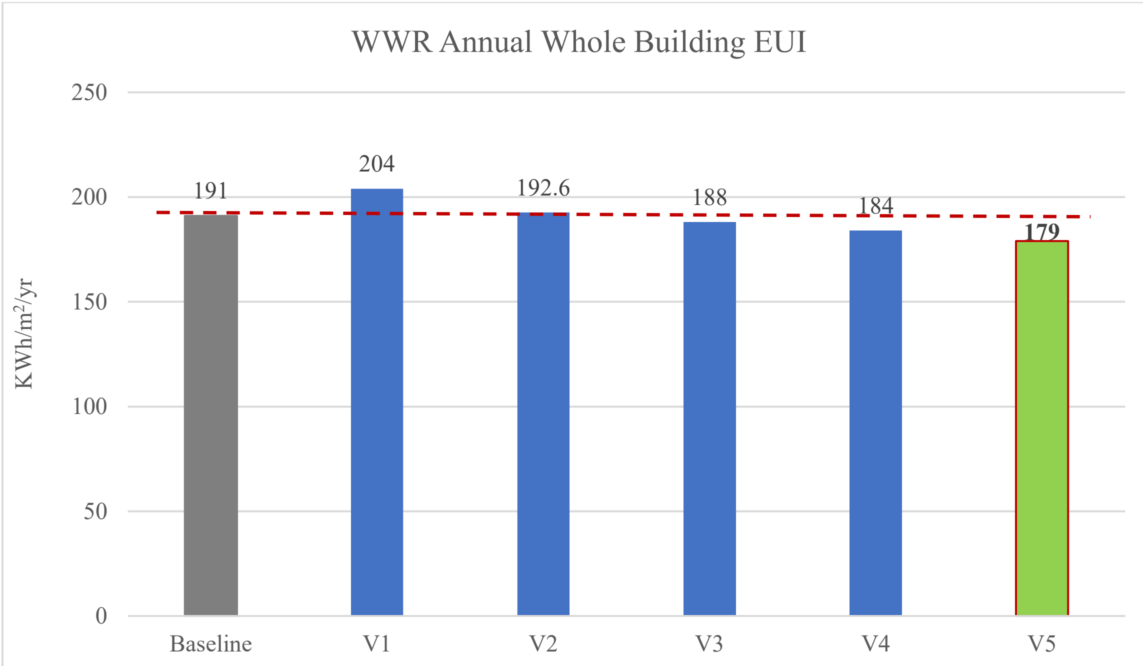

Figure 131. EUI results for parametric WWR design iterations.

Parametric Systems Modeling Results

The next set of parametric energy modeling analysis encompassed a thorough examination of building systems variables. The simulation results were based on an iterative singular building system variable evaluation. The results encompassed energy performance data for the following options: building envelope, HVAC systems, DHW systems, glazing systems, lighting systems, and space-conditioning schedules. Whole building Energy Use Intensity (EUI) was employed as the primary performance metric to compare and evaluate the various simulated parametric building systems iterations.

Building Envelope Iteration Results

The first set of parametric building system modeling scenarios explored the impact of building envelope variations on energy consumption in a typical multi-family apartment building. The modeling and simulation analysis examined a specific typology of envelope construction, predominantly employed in Lebanese multi-family residential buildings, concrete masonry block units (CMU). The analysis used exterior wall thickness coupled with insulation as the primary independent variable to assess the impact of width variation on energy consumption in a typical apartment building block. All other baseline massing parameters retained the same properties. All modeled iterations yielded lower energy consumption energy than the baseline model. Simulation findings revealed an 18% to 19% reduction in energy consumption compared to the baseline condition. To that end, the double cavity CMU walls generated slightly more energy reductions than the single width CMU walls utilizing much thinner wall assemblies and wall thickness (Figure 132). Nonetheless, results revealed negligible energy reduction variation amongst the modeled iterations.

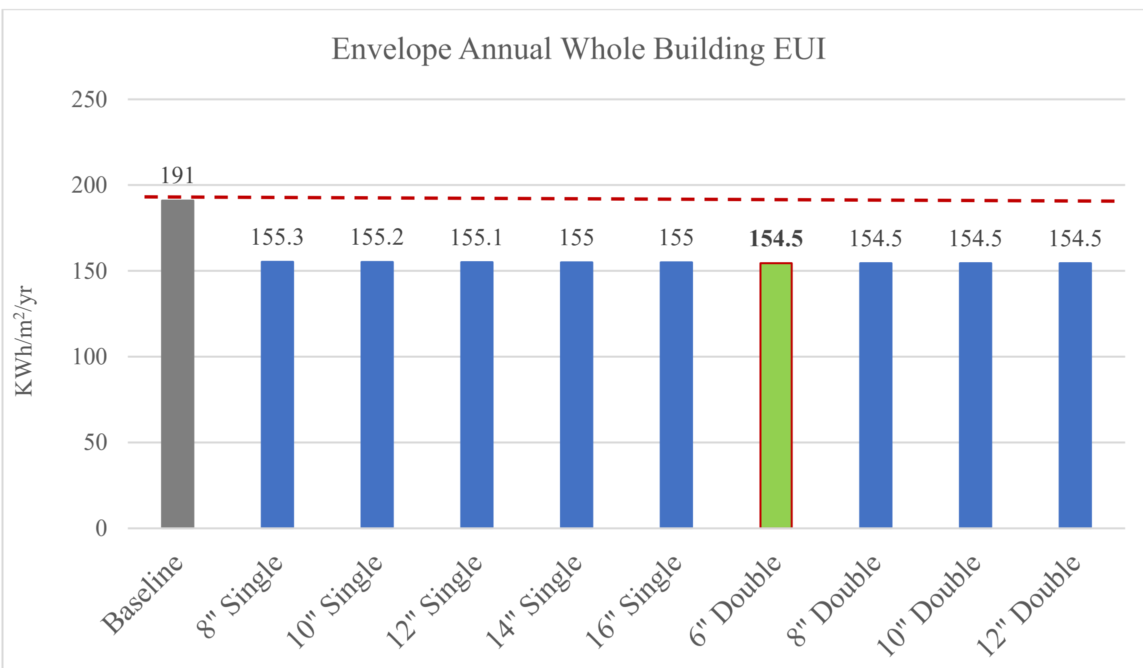

Figure 132. EUI results for parametric building envelope systems iterations.

HVAC Iteration Results

The second set of parametric building system modeling scenarios examined the effect of HVAC system variations on energy consumption in a typical multi-family apartment building. The analysis examined a series of HVAC systems, including ground source heat pumps (GSHP) and air source heat pumps (ASHP), determined to be the most appropriate systems for the Lebanese climate and residential building typologies. The modeling analysis evaluated HVAC system variations as the primary independent variable to assess the impact on energy consumption in a typical apartment building block. All other baseline parameters were kept the same. All modeled iterations consumed less energy than the baseline model. Simulation results revealed a 5% to 20% reduction in energy consumption, compared to the baseline condition, based on the different HVAC typologies. The GSHP-V1 employing a dedicated outside air system (DOAS) with a fan coil unit (FCU) yielded the largest energy reductions from the baseline at 20% (Figure 133). To that end, GSHP systems performed more optimally than ASHP, yielding larger energy reductions.

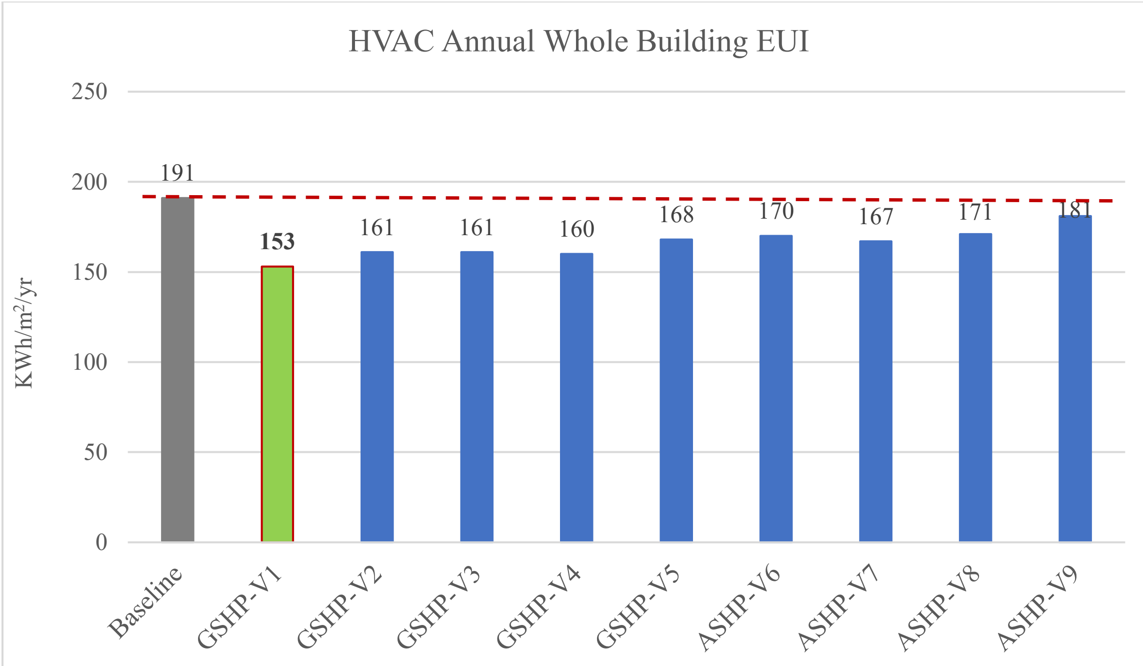

Figure 133. EUI results for parametric HVAC systems iterations.

DHW Iteration Results

The next set of building system scenarios investigated the impact of DHW upgrades on energy consumption. The parametric model analyzed a heat pump system, deemed the most appropriate system for residential apartment buildings in Lebanon. The upgraded DHW system yielded a 6% reduction in energy consumption compared to the baseline model.

Glazing Iteration Results

Glazing system upgrades were evaluated next to assess their overall impact on energy use. Glazing specifications were the main independent variables measured against the building energy use intensity. All upgraded modeled glazing iterations generated lower EUIs than the baseline model, ranging from 4% to 4.4% (Figure 134). To that end, the triple pane windows with two Low-E coatings and Argon Gas (V8) yielded the largest energy reductions. Nonetheless, the variance between all eight modeled iterations was negligible.

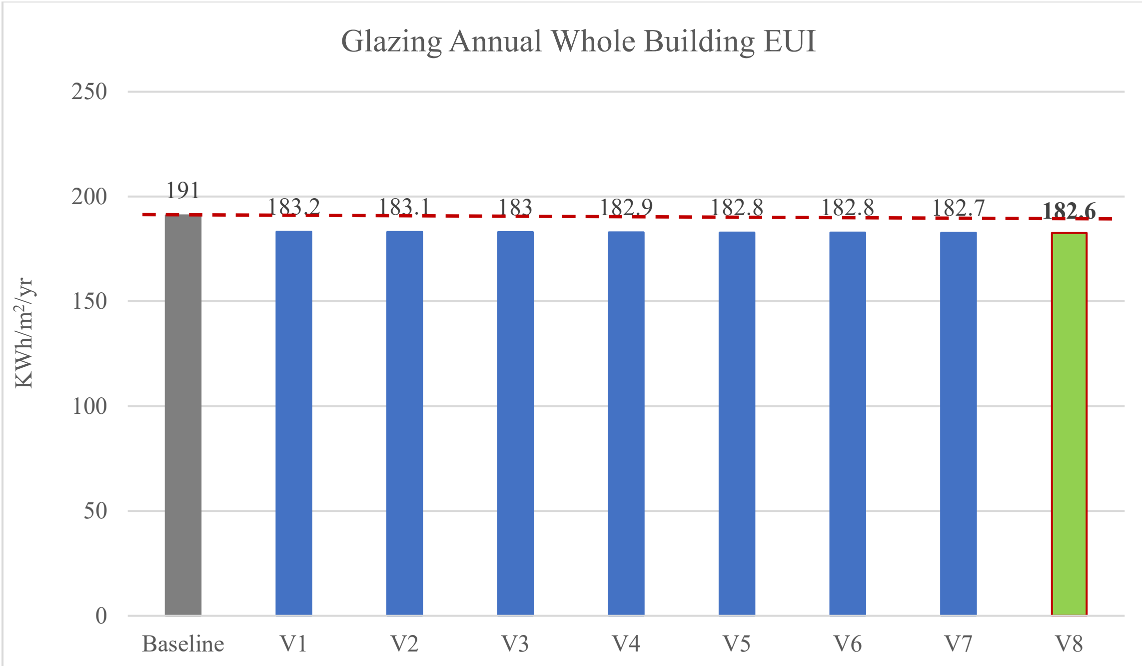

Figure 134. EUI results for parametric glazing systems iterations.

Lighting Iteration Results

The next set of building system scenarios investigated the impact of lighting system and equipment upgrades on energy use. The integration of daylight sensors, occupancy sensors, and lower lighting power density (LPD) reduced energy use by 11% compared to the baseline.

Space-Conditioning Schedule Iteration Results

The last set of building system variables examined the effect of space-conditioning schedule variations on energy use. The analysis assessed the impact of setpoint and setbacks variations on energy use intensity. Findings revealed a 6% reduction in energy consumption with heating and cooling setpoint and setback variations.

Discussion

Findings from the parametric modeling analysis of design and building system variables revealed a broad spectrum of energy consumption impacts. The parametric iterative modeling analysis evaluated correlations between upgraded architectural variables and energy performance. Results varied significantly between architectural design and building system variables. Simulation data showed a stronger connection between building system upgrades/variations and overall whole building energy use intensity. However, certain architectural design variations did have an impact on energy consumption in the building. In aggregate, eleven architectural parameters were modeled and simulated, encompassing five architectural design and six building system variables. Overall results revealed energy consumption reductions ranging between 0.5% and 20% over the baseline EUI. The next section outlines major findings from each of the modeled categories, including architectural design and building system variables.

Building Design Variables

The effect of individual architectural design modifications on energy use in a standard multi-family apartment building fluctuated amongst the various simulated options. Some yielded higher energy use, while others consumed less energy than the baseline. To that end, the highest performing option was selected from each design iteration for sake of comparison and analysis (Figure 135). Two out of the five modeled design variables yielded slightly larger energy consumption ranging between 0.2% and 1.6% over the baseline. The majority of the modeled design variables (three out of five, 60%) produced energy use reductions ranging between 0.3% and 6% over the baseline EUI. The most effective architectural design variable encompassed window to wall ratio modifications

(V5) followed by façade design iterations (NS V1). On the other hand, the least effective strategy entailed building massing/footprint variations, whereby results revealed a spike in energy consumption compared to the baseline compact square building footprint.

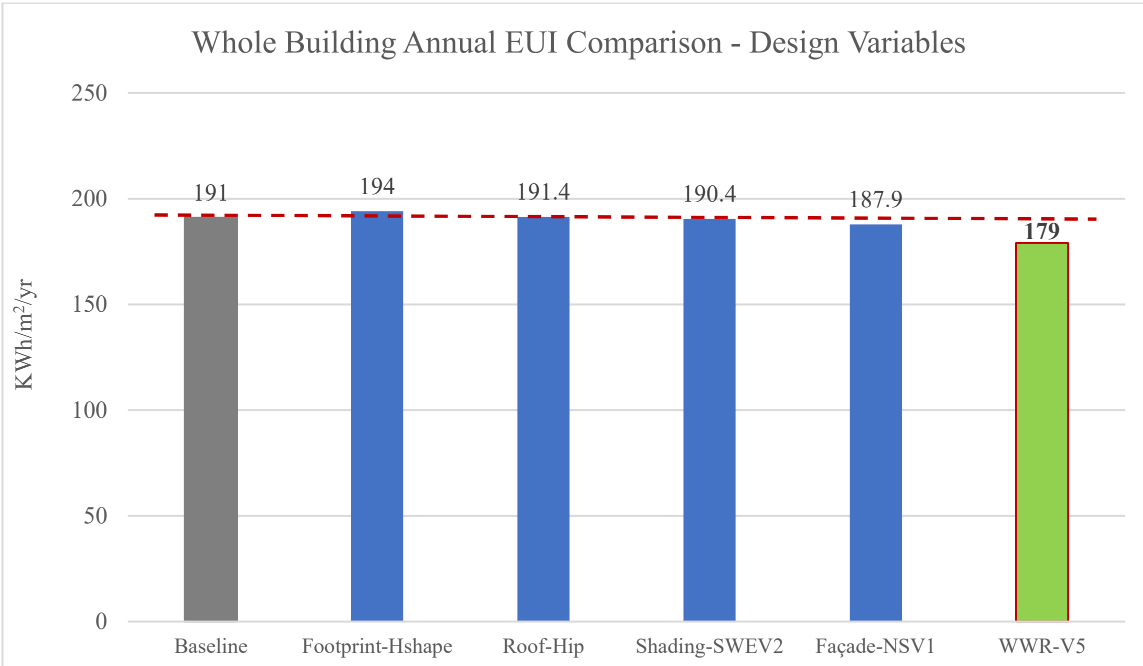

Figure 135. Energy use intensity for identified optimal building design variable runs.

The impact of design variations on energy use intensity wasn't as significant as anticipated, as evident in the parametric simulation results. Given the nature of selected archetype, design modifications were limited as to fit existing trends and building norms. The main premise of the research targeted standard low income to middle income residential blocks. As such, design alterations and exploration were limited in nature as to ensure the viability, applicability, and feasibility of the proposed solutions. Moreover, design parameters such as siting and orientation didn't play a major role due to existing land constraints/availability and density considerations within Lebanon's residential market. The research aimed to explore design solutions that afforded stakeholders flexibility and freedom as it pertains to applicability and feasibility, regardless of site conditions and land constraints. Nonetheless, the baseline model took into consideration optimal orientation and siting conditions in the targeted area of study. When assessing the efficacy of design modifications, heating and cooling loads were primary drivers of energy use within the building accounting for 33.5%, followed by equipment at 26.7%, and lighting at 24%. As such, the most optimal design variables were options that impacted those loads. The performance of the design variable runs is outlined in the section below.

Building Footprint and Massing. Four options were modeled, examining diverse deviations from the square baseline footprint. None of the modeled iterations yielded energy reductions. Nonetheless, the H-Shape option yielded the best results in terms of overall energy performance amongst the 4 simulated variations. However, findings revealed a 1.6% increase in energy use over the baseline scenario. Altering the building footprint caused a spike in energy consumption ranging from 1.6% to 11.5%. Deviating from a compact square footprint exposed the building to higher energy loads and affected its thermal performance negatively. The more surface area the building had the more heat gains and losses occurred throughout the envelope. As a result, the baseline compact square option was the most optimal option in terms of overall energy performance.

Building Roof. Several roof shapes were examined to evaluate the correlation between roof typology and energy consumption. The hip and gable roofs option performed closely to the baseline flat roof condition. On the other hand, the mansard roof option consumed approximately 10% more energy than the baseline condition. Flat roofs have better thermal performance than pitched ones due to insulation and material differences. Unlike pitched roofs that employ cavity insulation systems pressed between ceilings joists, flat roofs have a membrane system applied atop rigid insulation boards, effectively eliminating gaps within the insulation layer. The result is a more efficient and insulated roof envelope.

Furthermore, since flat roofs must be covered with a roofing membrane by design, material choices are usually more efficient in terms of thermal insulation. For example, Ethylene Propylene Diene Monomer roofing membranes (EPDM) are significantly more energy efficient than their traditional pitched-roof counterparts (NREL, 2011). Accordingly, buildings with flat roofs tend to have lower overall cooling and heating demands.

Shading Systems. Various shading systems configurations were assessed to better understand their impact on energy consumption. Simulation results reveled negligible energy reductions. Most options performed similarly to the baseline model. Nonetheless, incorporating horizontal shading devices on the south façade coupled with vertical and horizontal devices on the west and east facades yielded a 0.5% reduction in overall energy consumption. These results could be attributed to the fact that the building has a low window to wall ratio, hence minimizing and neutralizing the impact of shading systems on thermal performance.

Façade Design. Multiple façade window design options were modeled to evaluate the impact on energy consumption. Results varied amongst the simulated options. Some options performed similarly to the baseline condition and others consumed more energy, ranging between 1.5% and 4.6%. The increases in energy consumption could be attributed to the options that included more glass surface area. One modeled option consumed 4.6% lower energy than the baseline and could be attributed to the reduction of the amount of glass used on the north and south facades as well as changing the orientation of the glazing planes toward facing east. This design modification minimized the amount of heat gains and losses through the north and south facades while allowing for eastern daylight to penetrate the building interior.

Window to Wall Area. Five WWR typologies were modeled and evaluated. Findings revealed energy reductions, ranging between 1.5% and 6%, in three of the five options, all with lower WWR ratios than the baseline condition. Simulation results showed a strong connection between varying south and east facing window area percentages and overall energy consumption. One run yielded higher energy use, 6.8% over the baseline, and could be attributed to the higher WWR percentages leading to increased heat gains and losses through the envelope. Nonetheless, one run performed slightly better, resulting in approximately 6% reduction in energy consumption. The run was modeled based on the following criteria: 11% south and west WWR and 0% north and east WWR. The removal of north and east facing glazing minimized heat gains and losses through the envelope, hence, reducing overall heating and cooling loads and reducing the building's annual whole energy use intensity. Nonetheless, it's not a realistic option to exclude glazing entirely from the north and south facades.

Building Systems Variables

Simulation findings from the various building system parametric modeling runs showed a significant decrease in energy use from the baseline, ranging between 4.4% and 20%. The highest performing option was selected from each building systems iteration for sake of comparison and analysis Significant energy reductions were achieved employing building systems targeting primary space heating and cooling loads. Results revealed energy decreases amongst all simulated building system runs (Figures 136). Moreover, three out of the six modeled building system variables generated energy improvements higher than 10% over the baseline EUI, far exceeding the 0.3% to 6.3% energy reductions produced by the most optimal building design variables. To that end, the most optimal building system variables encompassed thermal envelope modifications (6” double cavity CMU wall with insulation) and HVAC upgrades (HVAC V1), each yielding 20% reduction in energy use over the baseline. Moreover, both upgraded systems generated a three-fold reduction in energy use over the most optimal building design variable.

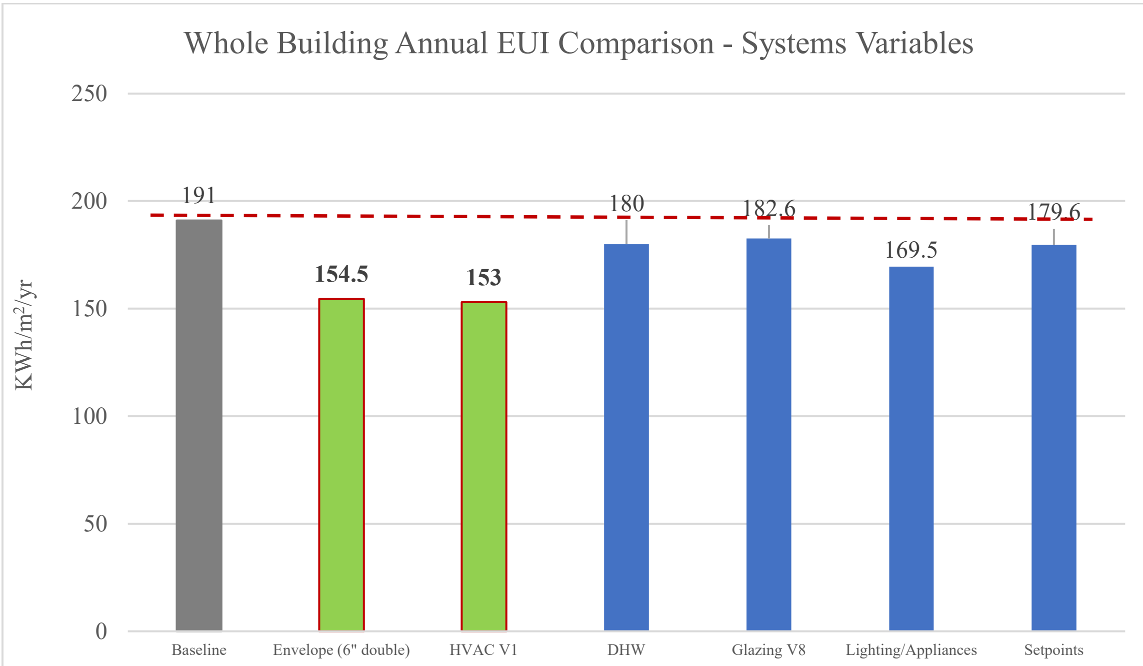

Figure 136. Energy use intensity for identified optimal building systems variable runs.

Building Envelope. Thermal load losses via the building envelope are estimated to range between 15% and 35%, based on the envelope surface area (EIA, 2017). Therefore, it’s imperative to design and specify building envelopes that perform optimally and deliver enhanced thermal performance to minimize a building’s energy loads. Nine exterior wall options were modeled, examining a variety of CMU wall construction typologies, using wall width and insulation as primary variables. All nine options yielded very similar results, ranging between 18% and 19% energy reductions from the baseline. To that end, the 6” single cavity wall with insulation would be the most optimal option given life-cycle, cost, and spatial considerations. However, given the current construction law incentives, the 6” double cavity wall with insulation would be the preferable option (Figure 137). Findings revealed no significant variation in energy use amongst the various simulated wall assemblies. Nonetheless, the additional thermal mass coupled with insulation were primary contributors to the improved energy performance. The increased R-values provided for enhanced thermal performance by minimizing heat gains and losses through the building envelope. The result is an airtight building envelope that significantly lessens overall energy loads, driving a 19% reduction in energy use intensity from the baseline condition.

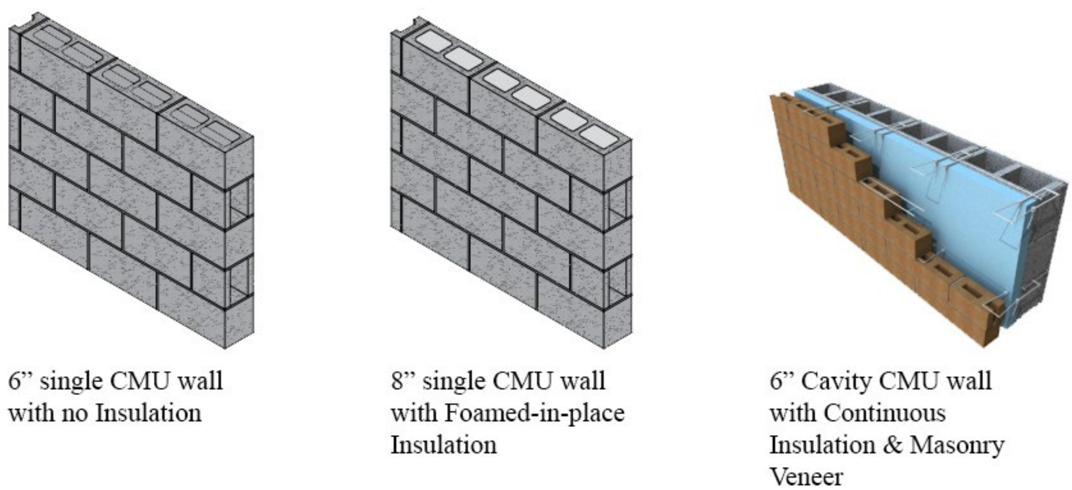

Figure 137. Wall assembly construction typologies (courtesy of NCMA)

HVAC. Building heating and cooling loads constitute about half of the energy loads in a residential structure (EIA, 2009). Nine HVAC options were modeled, evaluating various iterations of ground source and air source heat pump systems. It's imperative to employ high performing energy efficient HVAC systems to significantly impact energy consumption. Simulation results revealed all nine simulated options performed better than the baseline condition, generating energy reductions between 5% and 20%. The ground source heat pump systems, specifically the dedicated outside air system with fan coil unit

GSHP option (V1), performed more optimally than the rest of the modeled HVAC systems. This is because ground source heat pump systems employ mechanisms that move/transfer energy in lieu of creating it utilizing earth as a heat sink and/or heat source, hence, providing a very consistent and stable thermal performance. Simulation results showed energy use reductions amongst the largest over the baseline compared to all modeled variables, including building design and systems. Most of the realized gains could be attributed to significant reductions in heating and cooling loads, considered the primary drivers of energy use in residential structures.

Domestic Hot Water. Water heating constitutes around 18% of the energy consumption in a residential structure, third behind space heating and cooling, lighting, and appliances (EIA, 2009). Simulation results revealed the heat pump system as the most optimal option, reducing energy use over the baseline by approximately 6%.

Glazing. Windows are considered one of the weakest thermal components of a building envelope. A standard residential structure loses around 10% of its heat through windows. It's critical that high-performance glazing systems are employed to achieve optimal thermal performance. Eight glazing options were modeled, evaluating various window specifications and typologies. Upgraded parameters included U-values, solar heat gain coefficients, and most importantly, the number of windows panes and insulation. The low emissivity triple pane argon filled window option (V8) performed most optimally, reducing energy consumption by 4.4% over the baseline.

Lighting/Equipment. Lighting and equipment energy loads are one of the main drivers of energy consumption in a residential structure. Employing efficient appliances and lighting practices is paramount to achieving optimal performance and minimizing overall building energy loads. The modeling analysis encompassed an examination of the following lighting typologies: daylight sensors, occupancy sensors, and lower lighting power density (LPD). Simulation results revealed a significant improvement in energy performance, generating an 11% reduction in energy use over the baseline. The adopted strategies were instrumental in reducing lighting loads and overall annual energy use intensity.

Conditioning Setpoints & Setbacks. Setpoint and setback schedule modifications are often overlooked as viable strategies to alter energy consumption patterns. However, it's one of the very effective strategies in reducing energy use without significant physical investments and system upgrades. This behavioral and adaptive change is one of the most effective measures towards providing an optimal thermal environment. Establishing a defined programmed preset schedule, with lower-higher heating and cooling set points and setbacks, generated a 6% reduction in energy consumption over the baseline.

Building Optimization

The next stage of the analysis entailed a cumulative iterative parametric examination of all significant energy-reducing building variables, defined as generating at least 5% energy reduction from the baseline model. Energy use intensity was used as the primary energy performance indicator. The analysis sought to evaluate the collective impact of modeled variables on energy consumption in a residential apartment building.

Parametric Run 1 – Design Optimization

Simulation findings from the various building design parametric modeling runs showed an energy consumption reduction from the baseline ranging between 0.3% and 6%. The only design option yielding energy reductions above 5% was the window to wall ratio option that included windows only on the south and west facades of the buildings at an 11%WWR. This was deemed as un-realistic approach given the existing industry norms and building practices in Lebanon, where glazing is expected and included on every building façade. No design options were employed or adopted beyond this point in the optimization analysis. The assumed baseline model design parameters were effectively considered the most viable and efficient in terms of energy use.

Parametric Run 2 – EUI to Cost Optimization

The next phase of the parametric energy analysis sought to examine the most optimal EUI to cost option. The simulation used the baseline model as the benchmark condition for the optimization analysis. The Cove simulation platform evaluated 61 iterations and 18,432 possible combinations to generate the most optimal *Cost vs Energy Bundle*. The iteration that generated the most optimal energy to cost results encompassed the following upgrades: daylight and occupancy sensors, high performance HVAC systems, high performance glazing systems, and enhanced roof and wall insulation values. The optimized bundle generated an EUI of 130 kWh/m^2/yr, a 32% reduction from the baseline (Figure 138), while costing an additional $18,000 for the upgraded systems, with a payback period of 5.5 years. However, the optimized run generated an EUI 4% higher than the 2030 baseline threshold. Nonetheless, the run generated 57% less carbon dioxide emissions (39.67 Tonne/CO_2e/yr) than the baseline run and 34% less than the 2030 baseline.

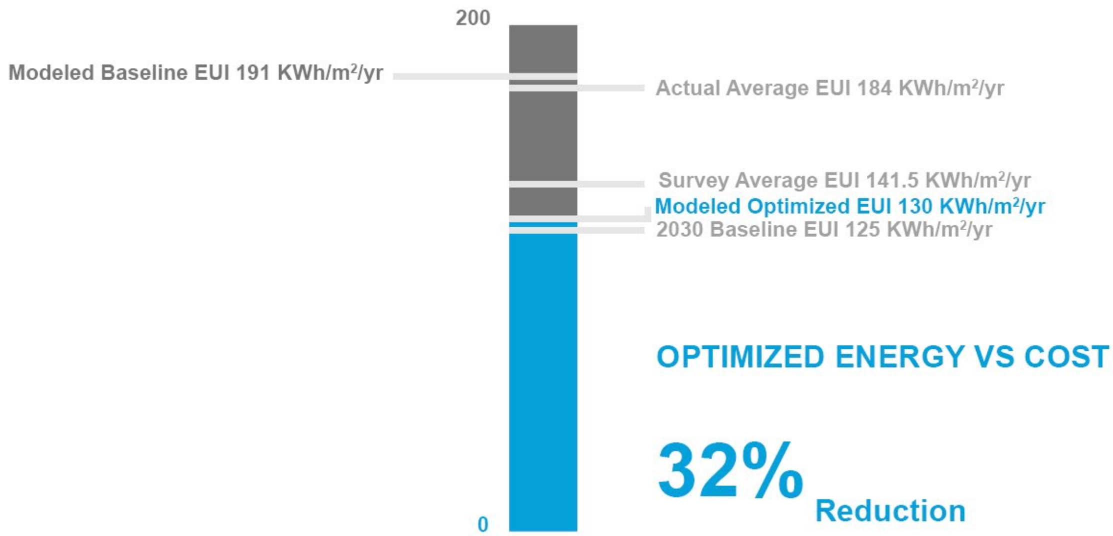

Figure 138. Optimized EUI vs Cost chart showing a 32% reduction in energy use from the baseline

Parametric Run 3 – Building Energy Code Optimization

The next phase of analysis encompassed an optimization approach of building energy codes employed in the baseline model, which used ASHRAE 2007 (the American Society of Heating, Refrigerating and Air-Conditioning Engineers) and IECC 2009 (The International Energy Conservation Code) to set the standards utilized to determine the minimum values of the various building systems. ASHRAE and IECC represent industry guidelines used to regulate minimum energy performance levels in buildings. To that end, ASHRAE 2007 and IECC 2009 are currently being used within the residential industry in Lebanon as the benchmark. This phase of the parametric analysis encompassed an optimization approach of building energy codes to reflect a more current and UpToDate standard. All baseline assumptions were upgraded to meet the standards and guidelines set forth in ASHRAE 2019 and IECC 2021. Simulation results yielded a 36.5% reduction in energy use over the baseline and 3% below the 2030 baseline threshold (Figure 139).

Moreover, the optimized energy code run generated 45% less carbon dioxide emissions than the modeled baseline run and 2% less than the 2030 baseline.

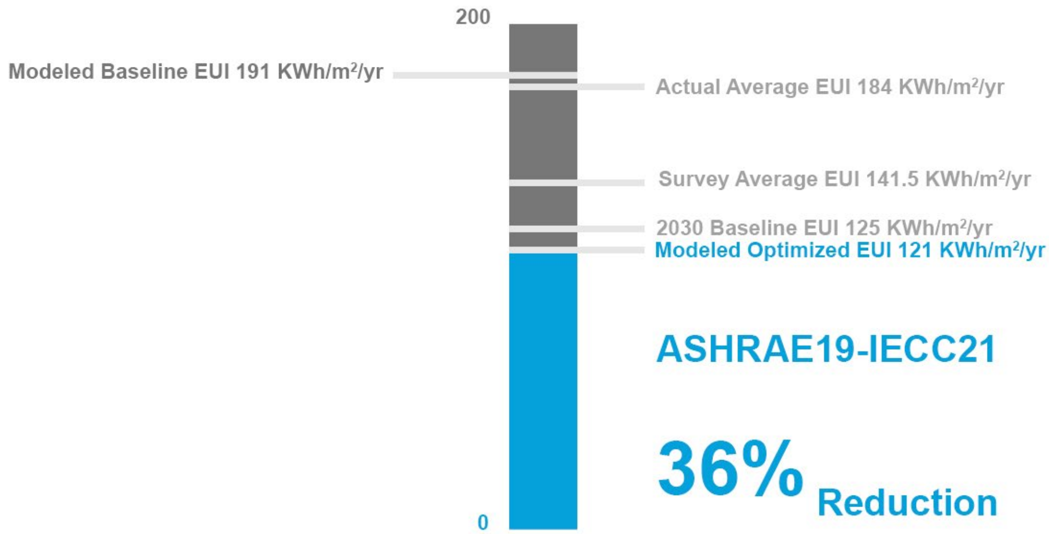

Figure 139. Optimized code chart showing a 36.5% reduction in energy use from the baseline

Parametric Run 4 – Building Systems Optimization

The next phase of analysis encompassed systems optimization. Individual building systems simulation results yielded energy consumption reductions ranging between 4.4% and 20% compared to the baseline condition. Eighty three percent of all building system variables yielded energy reductions above the 5% threshold set forth as a required benchmark for optimization inclusion. The only design option yielding energy reductions below 5% was glazing upgrades. Nonetheless, it's a widely adopted existing building industry practice to install upgraded windows when viable in new buildings. Hence, it will be included in the systems optimization modeling and simulation analysis. A new energy model was simulated including the sixth highest performing building system variables (envelope, HVAC, DHW, glazing, lighting, setpoints – Figure 136) to assess their cumulative impact on energy consumption in a standard Lebanese apartment building. All baseline design parameters were kept the same.

Table 12. The highest performing building systems variables chosen for optimization modeling

Category	Optimized Energy Model Specifications
Building Envelope	85 PCF 6” Double CMU cavity wall with 3.5” polyiso insulation
HVAC System	GSHP with DOAS System and Fan Coil Unit
DHW System	Heat Pump
Glazing	Triple pane with two Low-E coatings and Argon Gas
Lighting/Equipment	LED lighting with daylight and occupancy sensors/Efficient Appliances
Setpoints & Setbacks	Efficient Schedule Variations and settings

Simulation findings of the cumulative top sixth highest performing buildings systems variables yielded a 41% reduction in energy consumption over the modeled baseline scenario. The optimized simulated run produced an EUI of 113 kWh/m^2/yr, 10% below the 2030 baseline threshold, 20% less than the Lebanese surveyed average EUI, and 38% below the actual average EUI of multi-family residential buildings in Lebanon (Figure 140). Furthermore, the optimized systems run generated 46.5% less carbon dioxide emissions (49.4 Tonne/CO_2e/yr) than the modeled baseline run (92.5 Tonne/CO_2e/yr) and 17.6% less than the 2030 baseline of 60 Tonne/CO_2e/yr. The impact of the cumulative building systems upgrades to the baseline model was evident and significant. The optimized run generated approximately 41% reduction in energy consumption over the baseline EUI, an imperative benchmark towards a Net Zero approach.

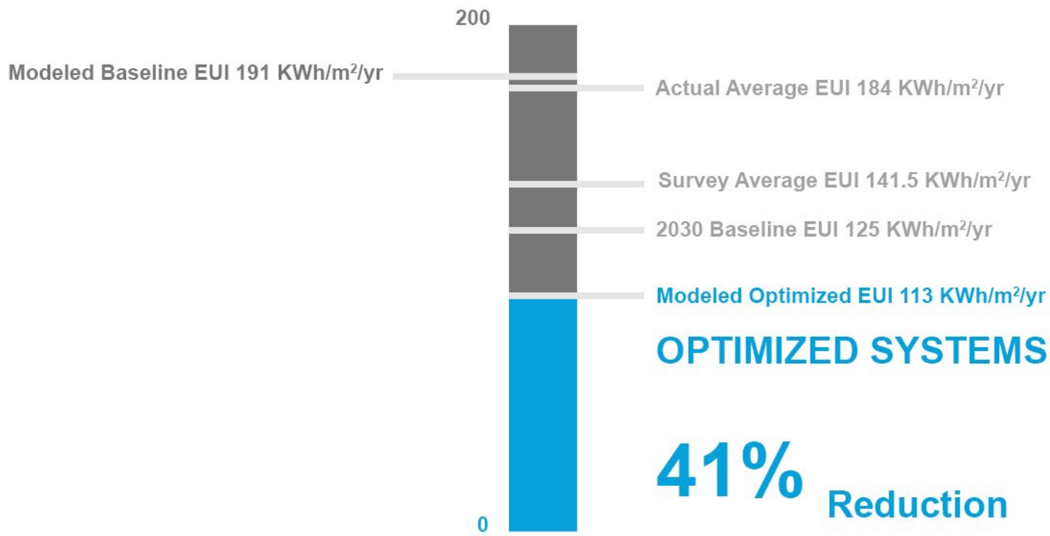

Figure 140. Optimized chart showing a 41% reduction in energy use from the baseline

Parametric Run 5 – Building Systems + Energy Code Optimization

The next phase of energy simulation analysis encompassed a combined optimization method of cumulative enhanced building systems, from *Parametric Run* 4, plus upgraded energy code (ASHRAE 2019 and IECC 2021), from *Parametric Run* 3. The analysis sought to assess the impact of the cumulative all-inclusive approach on energy consumption in a multi-family apartment building in Lebanon. Simulation results generated a 50% reduction in energy consumption over the baseline and 22% below the 2030 baseline threshold. The parametric run yielded an EUI of 97 kWh/m^2/yr, compared to the baseline EUI of 191 kWh/m^2/yr (Figure 141). Moreover, the run generated 57% less carbon dioxide emissions (39.1 Tonne/CO_2e/yr) than the modeled baseline run (92.5 Tonne/CO_2e/yr) and 30% less than the 2030 baseline. In aggregate, the parametric run reduced energy consumption over the baseline's EUI by half, paving the way to a Net Zero-Ready building.

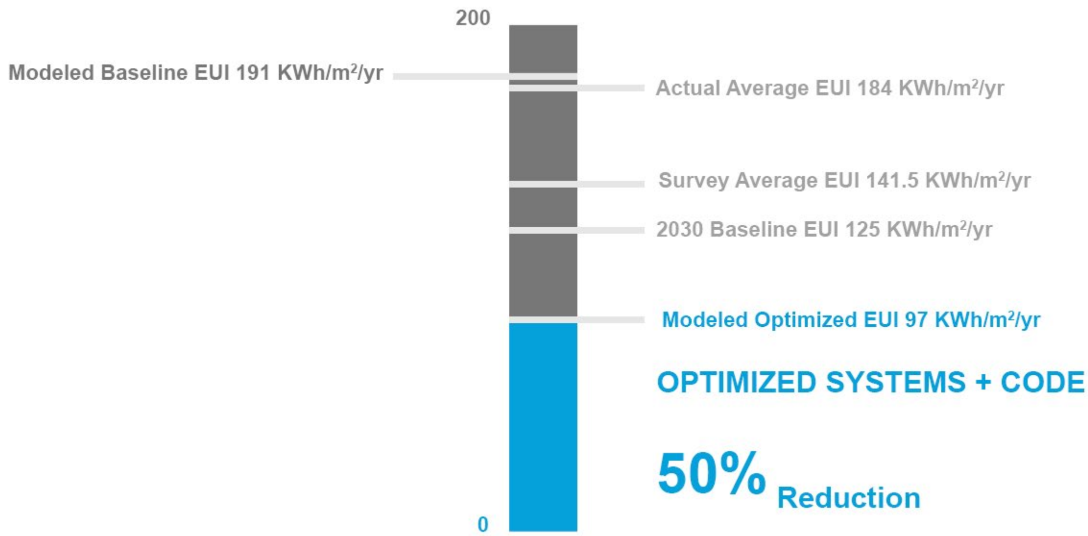

Figure 141. Optimized systems+code chart showing a 50% reduction in energy use from the baseline

Parametric Run 6 – Building Optimization + Solar Thermal DHW

A solar thermal hot water system was employed next, using the previous run *(#5)* metrics, to evaluate its impact on overall performance and energy use intensity. Simulation results yielded a 56% reduction in energy use over the modeled baseline and 32% below the 2030 baseline. The solar thermal system offset nearly 100% of the domestic hot water needs.

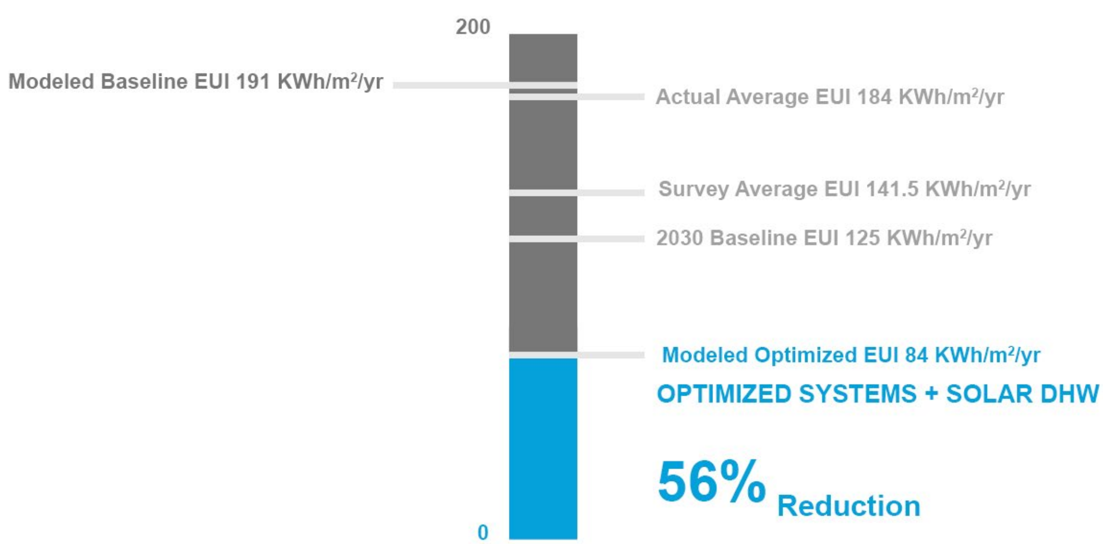

Figure 142. Optimized Solar DHW+run 5 chart showing a 56% reduction in energy use from the baseline

Parametric Run 7 – Net Zero Energy (NZEB) PV Optimization

The last phase of the parametric energy analysis examined Net Zero Energy (NZE) optimization utilizing on-site energy generation as the primary intervention mechanism to offset energy use in the building. To that end, the highest performing iteration *(Parametric Run #6 - 84 kWh/m²/yr)* was selected for the Net Zero energy optimization analysis since it reduced the building's EUI by more than half below the modeled baseline scenario. Design optimization coupled with optimal integration of passive and active strategies reduced the building's total energy loads by 56%. Thereafter, the remaining loads were addressed by the deployment of a Photovoltaic (PV) system. Hence, the significant energy load reduction paved the way to a smaller on-site renewable energy generation system. A 45KW PV system was employed for on-site energy generation (Table 13), sized based on the amount of energy consumed by the building annually (84 kWh/m²/yr at 134,000 KWh) and available roof area ($400m^2$). The south facing fixed roof-mount premium PV system occupied a surface area of 205 m^2 (50% of roof area) with a 20-degree solar panel tilt angle based on the latitude of the site. Mono Crystalline Silicon panels were used for their efficiency (10% system losses) and prevalence within the Lebanese renewable energy market, with a 19.4% capacity factor. Thereafter, the Net Zero Energy parametric run was simulated with the on-site energy generation component to assess the overall impact on the building's annual energy consumption and performance. Simulation results showed a significant drop in EUI compared to all previous parametric runs, due to PV offsets. The Zero Energy optimization run yielded a net EUI of Zero kWh/m²/yr, a 100% reduction from all previous parametric runs and the baseline (Figure 143). The deployment of the PV system offset the entire energy consumption of the building via the on-site production, hence, reducing the building's overall energy use intensity to Net Zero (Figure 144).

Table 13. PV system specifications

Category	PV Specifications
Sizing Criteria	Energy Loads: 134,000 KWh at 84 kWh/m²/yr 45 KW per apartment per day
System Design	8 separate units (1 per apartment)
Roof Area	205 m^2
PV System	• 8 Must-Pro inverters 5200w, 24Amp • 80 Longi Mono Crystalline Silicon panels, 545 watts each (10 per apartment) • 80 Gel Batteries, 150Amp (10 per apartment) • 80 Gel Batteries, 200Amp (10 per apartment) • 27KW nighttime capacity @ 10.22Amp per hour • 18KW daytime capacity @ 6.81Amp per hour • Module Type: Premium • Losses: 10% • Tilt: 15 degrees • Inverter Efficiency: 96%
Structure	Galvanized mounted structure roof installation
Cost	$8,800 per apartment

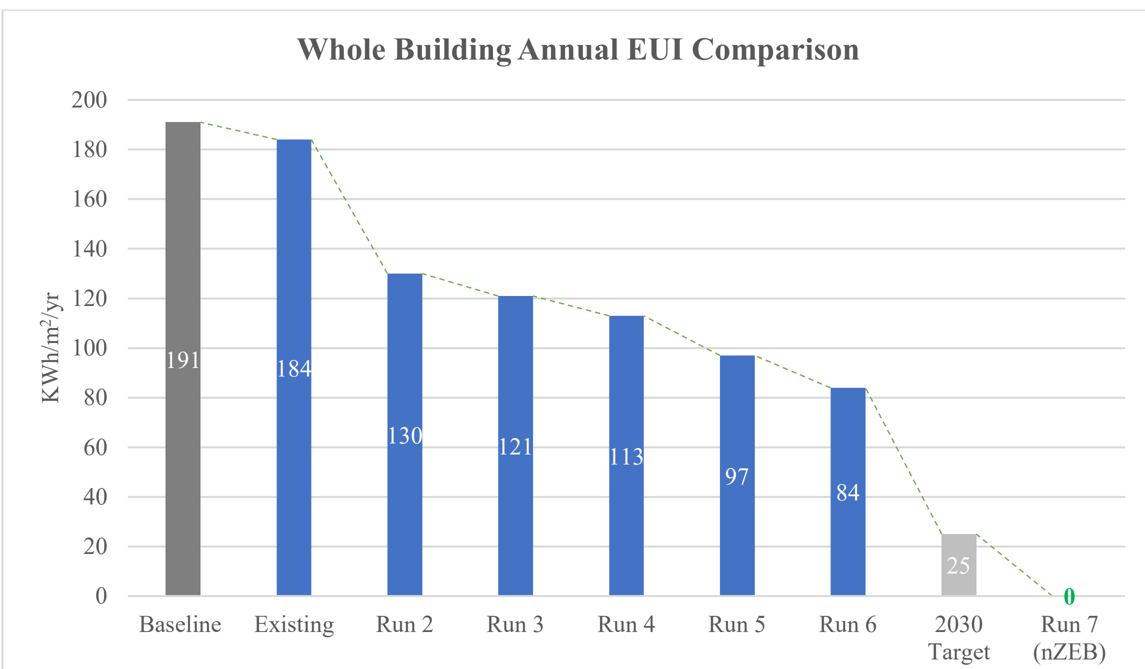

Figure 143. EUI comparison chart of all simulated parametric runs

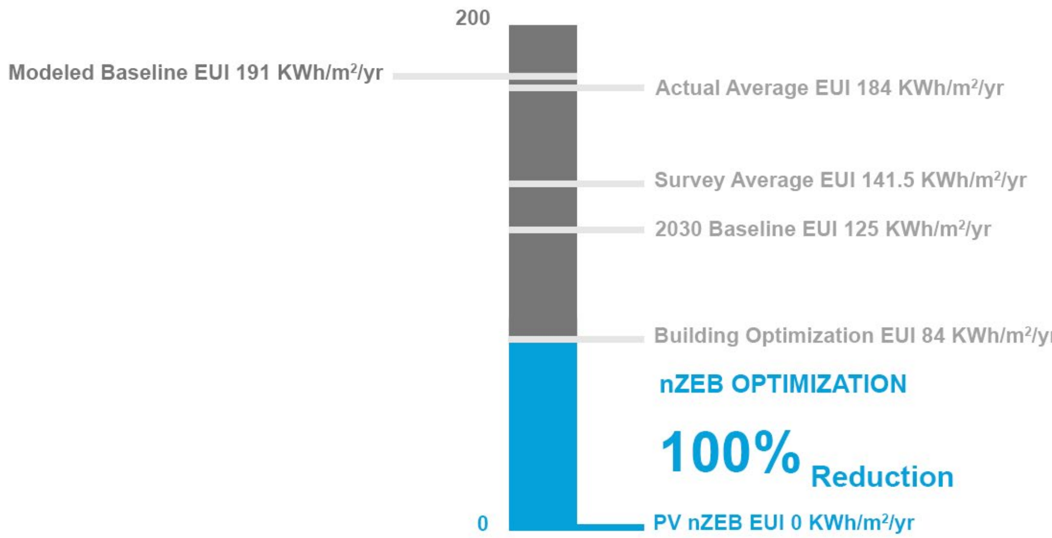

Figure 144. Optimized PV NZEB chart showing a 100% reduction in energy use from the baseline

In aggregate, the PV system accounted for 100% of the building's annual energy consumption, offsetting 84 kWh/m²/yr (Figure 145) of the building's overall EUI and generating approximately 134,000 kWh of electricity annually (Figure 146). Moreover, simulation results of the Net Zero Energy optimization revealed a 100% reduction in CO_2 emissions from the baseline, yielding Zero Tonnes of CO_2e/yr, eliminating the building's overall carbon footprint (Figure 146). Moreover, the Net Zero Energy optimized parametric run generated an equivalent of $10,000 in total annual energy cost savings, approximately $1,200 per apartment. The 45KW PV system is estimated to cost between $60,000 and $70,000 with a payback period around ten years. The building's total annual energy cost, after PV offsets and inputs, was Zero. Each apartment's annual energy cost was reduced to Zero dollars monthly, compared to the actual surveyed average cost of approximately $100 per month per household ($30 for subsidized public power supply and $70 for private generation). The net cost savings are a complete elimination of the private and public electricity utility bills, which are major drivers of financial burdens and strains in a typical household. The optimized Net Zero Energy cost savings are a game changer, offering households economic resiliency and security. The final EUI of Zero kWh/m²/yr, offset by PV production, paved the way to a Net Zero Energy building. Furthermore, the NZEB optimization simulation results produced an EUI 100% below the 2030 baseline and the 2030 Net Zero target metric of 25 kWh/m²/yr. Hence, the findings are in line for meeting and exceeding the 2030 Net Zero guidelines.

Net Zero Energy optimization simulation findings revealed equipment/plug loads (appliances, devices, cooking, and miscellaneous electric loads, etc.) as the most dominant energy end-users at 57%, followed by heating, cooling, and lighting loads respectively (Figure 148). However, in the case of many Lebanese households, space heating and cooling is also supplied by plug-in equipment, adding to the overall equipment load. Nonetheless, the PV system did offset all the loads by generating 84 kWh/m²/yr annually. As a result, annual energy costs were eliminated, hence, reducing the financial burdens of electric supply and reliance on unregulated private power generation. Furthermore, the Net Zero Energy optimization provided a more stable stream of electrical supply, enhancing household's resiliency to power outages, chronic blackouts, and unreliable power capacities. The Net Zero approach also afforded a higher level of resiliency against monthly climatic variations. To that end, monthly energy simulation results revealed the highest energy use during the month of January followed by August (Figure 149). Heating energy end-use dominated energy consumption during the winter months, spanning from November to April. On the other hand, cooling loads drove summer energy consumption from May to October. Lighting and equipment loads were also major drivers of energy consumption consistently throughout the year.

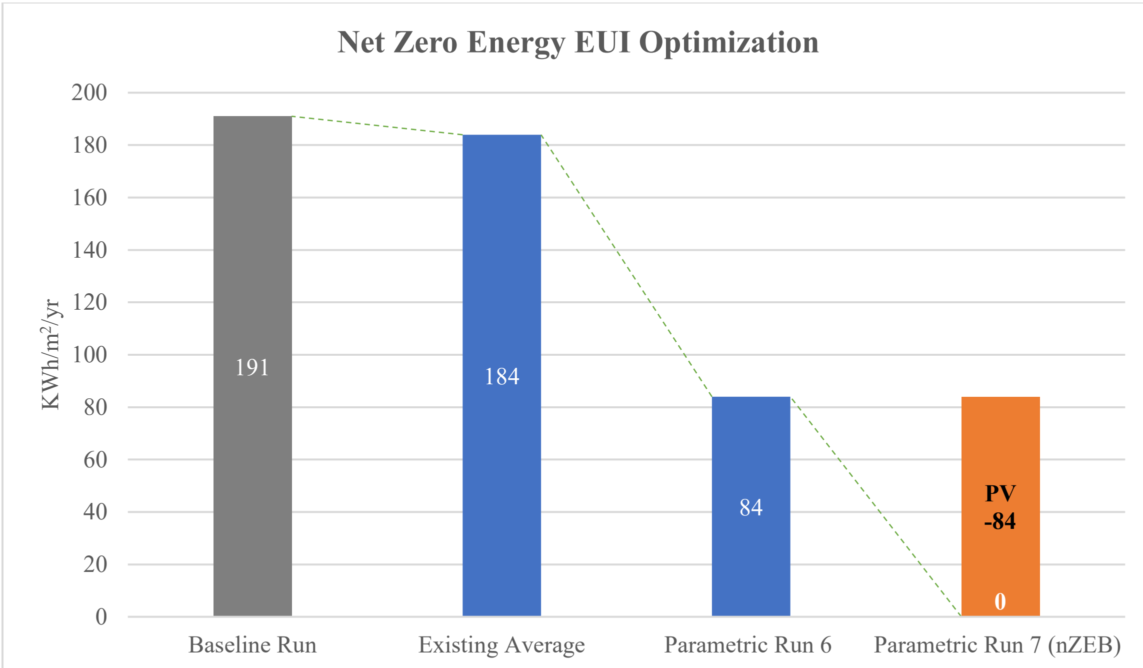

Figure 145. EUI chart showing the NZE optimization in reference to the baseline and parametric run 6

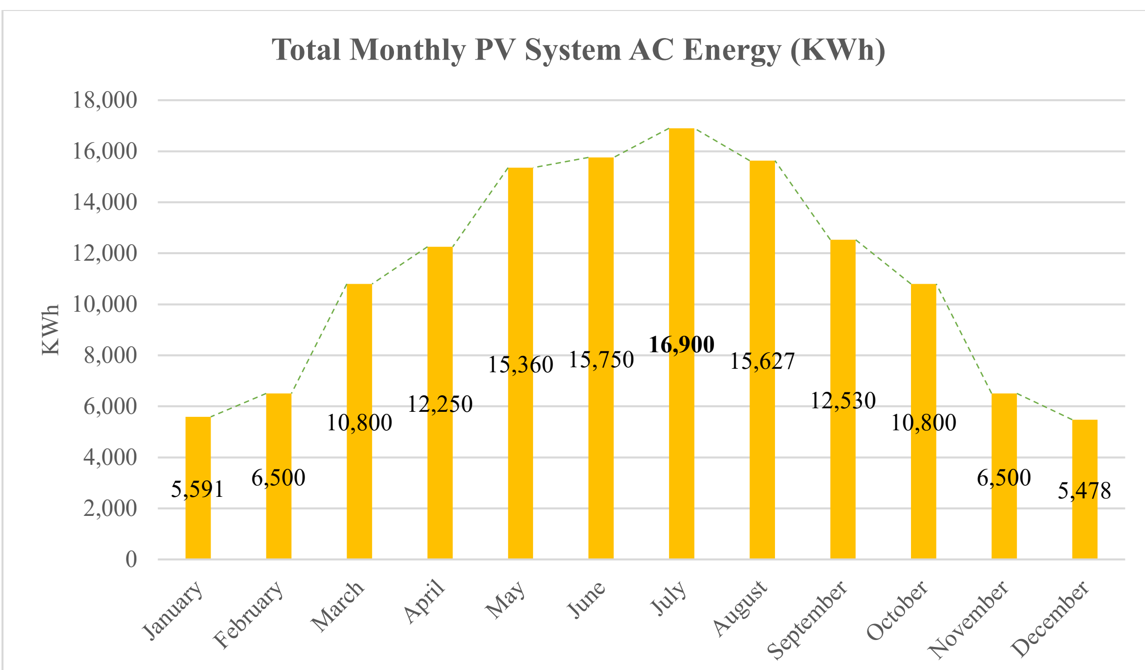

Figure 146. Chart showing total monthly amount of AC energy produced by the PV system

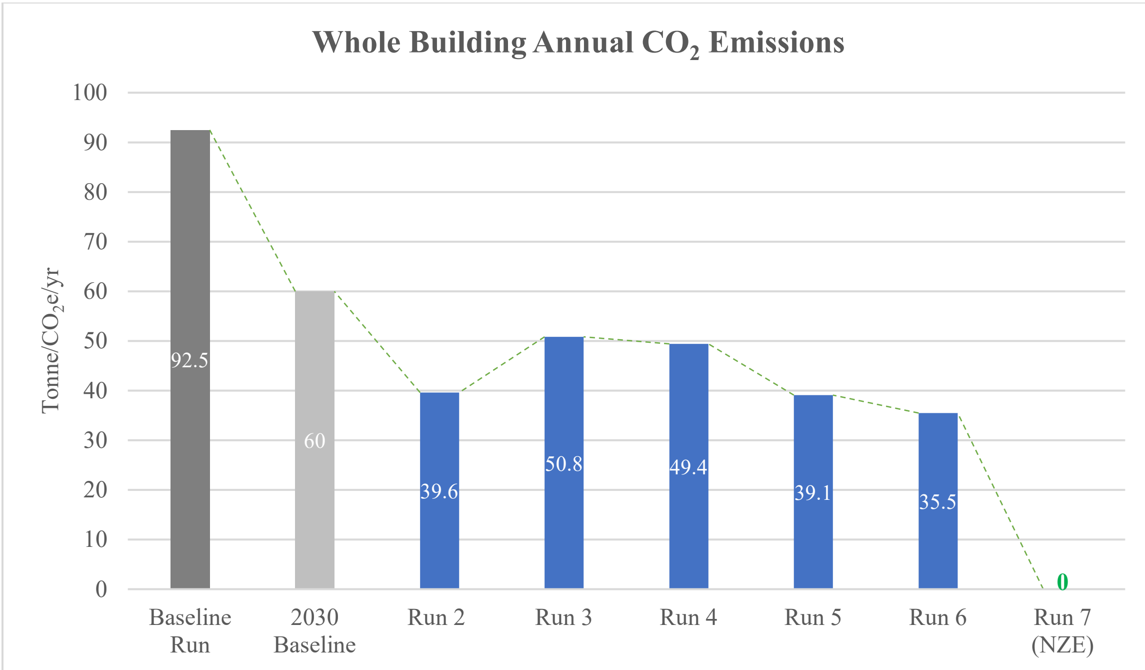

Figure 147. Chart showing CO_2 emissions across the baseline and all optimized parametric runs

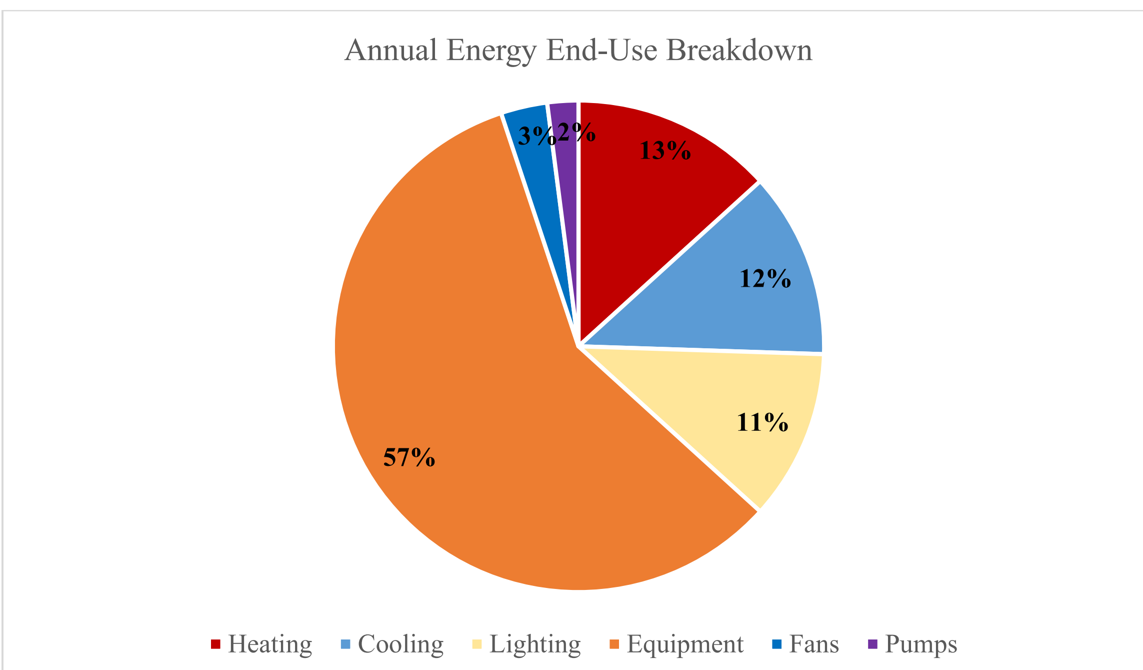

Figure 148. Chart showing annual EUI end use breakdown distribution percentages

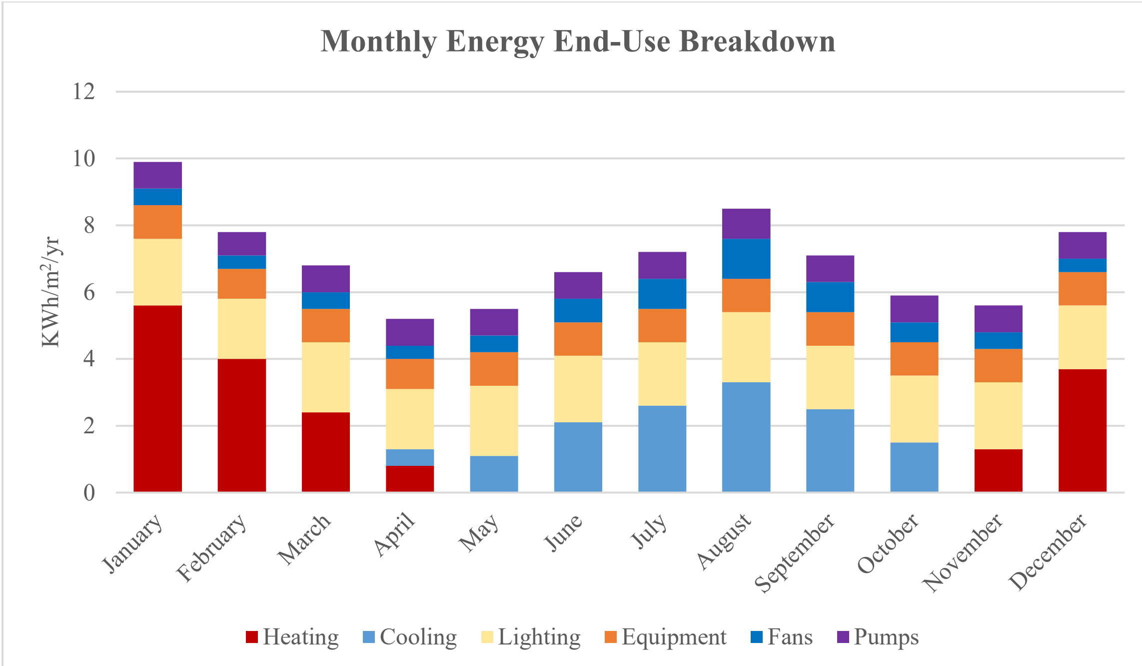

Figure 149. Chart showing total monthly energy end use breakdown

Net Zero Energy (NZEB) optimization results revealed peak heating system energy loads between October and March, while peak cooling loads were realized between April and October. Furthermore, ventilation loads (mechanical, natural, and infiltration) were most prevalent between April and October (Figure 150). That period also experiences higher air temperatures compared to the rest of the year, with temperatures peaking in July and August. Lighting and hot water loads were consistent throughout the year as shown in figure 148. Hourly simulation results showed peak heating loads between 8PM and 8AM, corresponding with the lower temperature profile during the nighttime. On the other hand, cooling loads spiked between 8AM and 8PM, coinciding with the period of the day with higher temperature and humidity profiles (Figure 151 & 152). The findings reinforce the need to adopt an annual comprehensive strategy dealing with energy loads in a sustainable and efficient manner. Moreover, lighting and hot water needs are critically important since they constitute a yearlong energy load demand. The NZEB approach provides a systematic approach to mitigating energy loads through the various seasons and times of day.

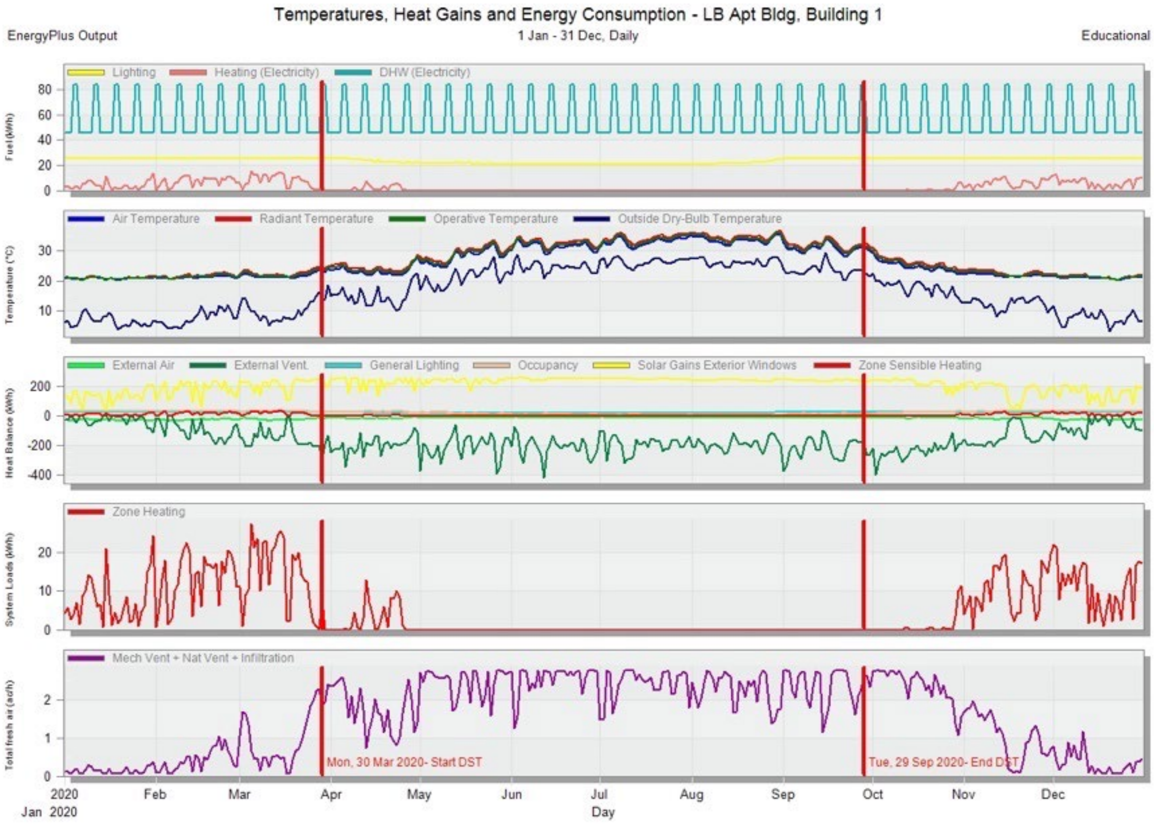

Figure 150. Temperatures, heat gains, and energy consumption monthly profile

It’s important to note that the specifications of the current PV system were based on the available roof area as well as the feasible amount of energy to be offset by the designated system to transition the building to a NZEB structure. The designated PV system was able to offset 100% of the building’s annual energy consumption, making it completely autonomous, especially with the integration of battery storage systems. Hence, transitioning the residential sector on Lebanon to Net Zero Energy is more than achievable and viable as an approach, financially and logistically.

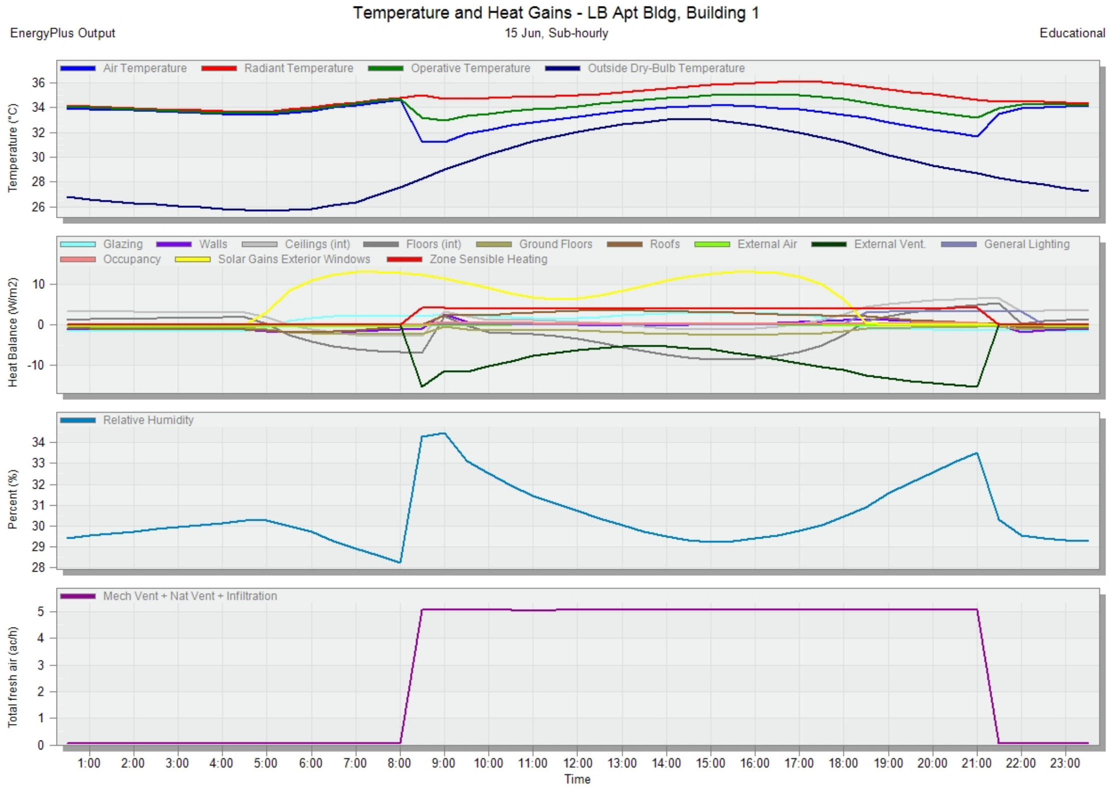

Figure 151. Temperature and heat gain hourly profile during peak summer day

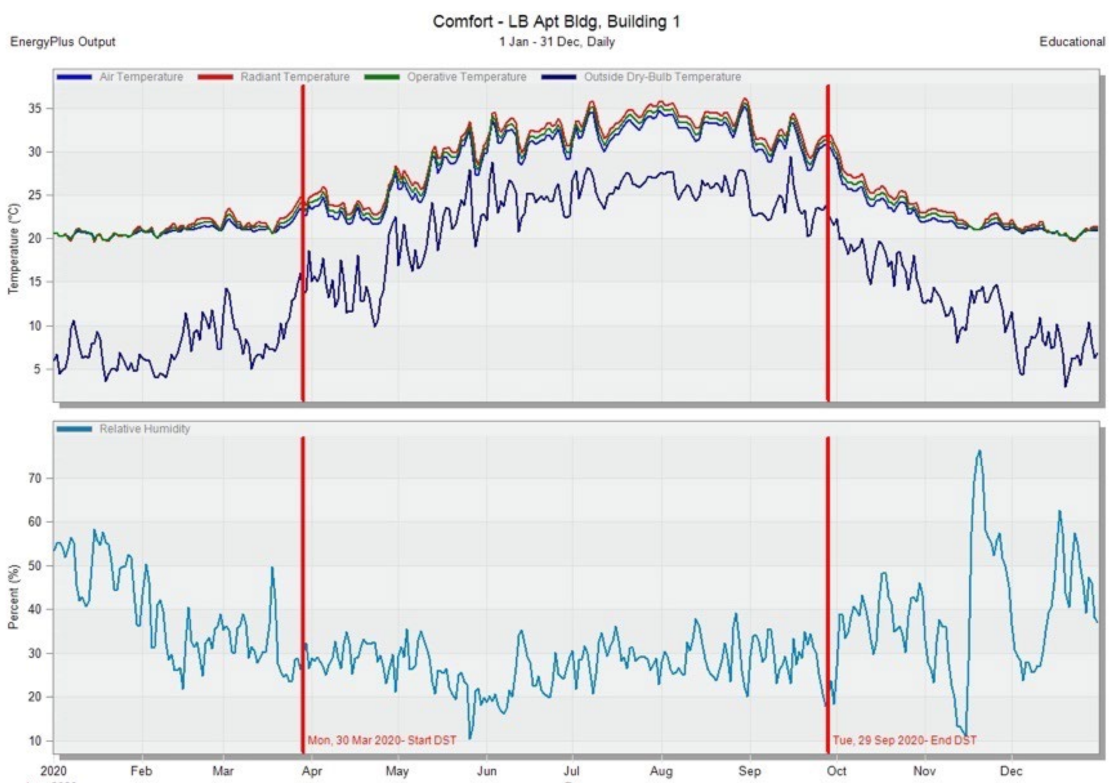

Figure 152. Daily temperature and relative humidity comfort profile

Psychrometric thermal comfort data from the Net Zero optimization parametric run suggest internal heat gain reduction as one of the primary design strategies to increase overall comfort in the building, followed by evaporative cooling and thermal mass coupled with night ventilation (Figure 153). Increasing the overall R-value and insulation levels of the building's thermal envelope is key to enhancing thermal comfort within the building. Hence, reducing internal heat gain via windows and external walls is paramount to ensuring optimal comfortable indoor conditions.

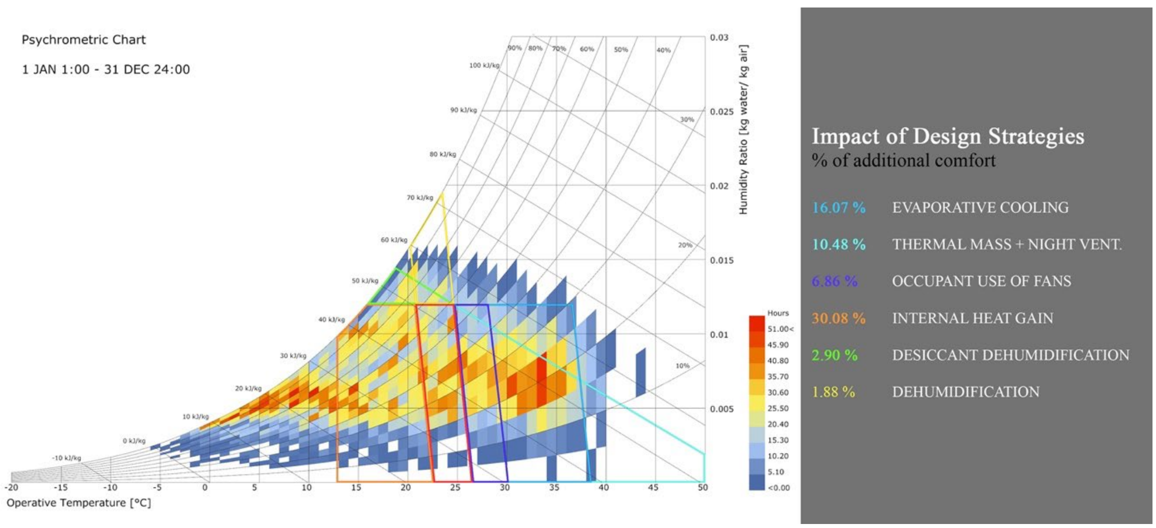

Figure 153. Psychrometric chart data showing impact of optimal design strategies on comfort

Simulation results of the Net Zero Energy optimization run yielded a 100% reduction in CO_2 emissions from the baseline, generating only 0 Tonne CO_2e/yr and in turn reducing the building's overall carbon footprint drastically. Embodied Carbon, which encompasses CO_2 emissions resulting from manufacturing, transportation, construction, installation, operations, maintenance, and end-of-life of building materials, is an essential global warming metric. To that end, embodied carbon was examined and recorded to better understand the impact of the various design/system strategies on greenhouse gas emissions and carbon footprint. The analysis encompassed three primary envelope components including wall insulation, glazing and roof assembly. Results show the NZEB iteration having slightly lower total embodied carbon emissions than the baseline (Figure 154). Nonetheless, coupled with significantly lower operational carbon emission and large energy consumption reductions, the NZEB parametric option performed considerably better than the baseline condition. Since most of the building's total embodied carbon is emitted early on during the production and manufacturing stage, it's imperative for it to be addressed meaningfully and holistically to reduce the building sector's overall carbon footprint.

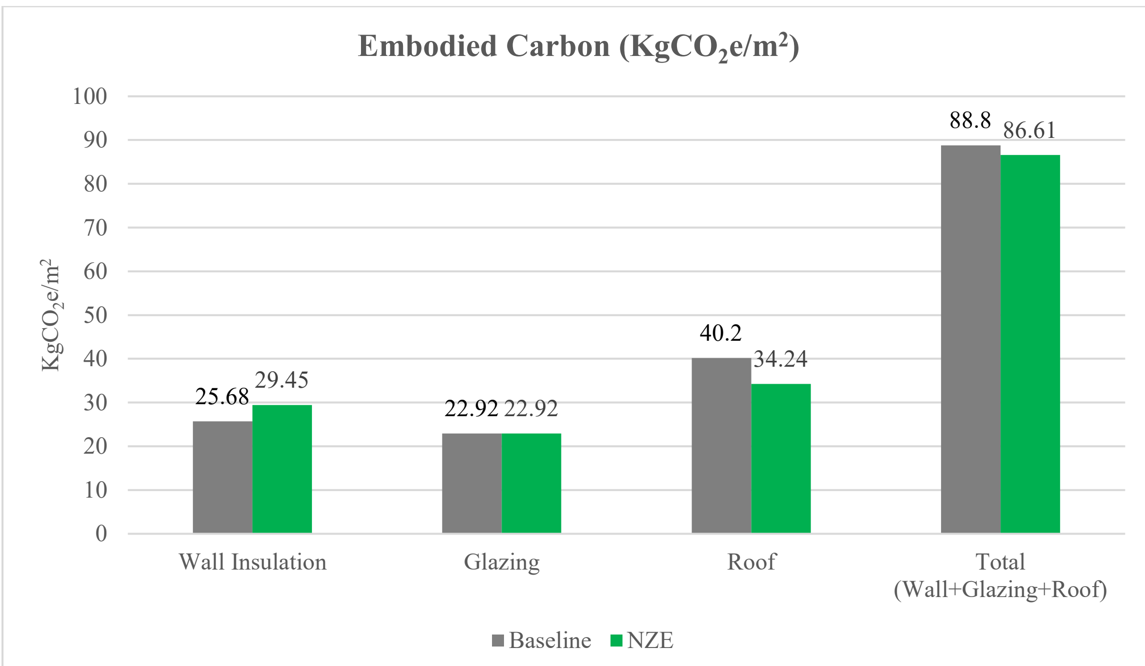

Figure 154. Chart showing building's embodied carbon (wall, glazing, roof)

One Click LCA was used as the primary life cycle assessment tool (LCA) to evaluate and examine the building's comprehensive life cycle impact using net carbon as the main metric. The building's upfront net carbon emissions (represented with letters A1-A5 in graph below) was 757,409 Kg CO_2e. Site operations and waste handling totaled 9,931 Kg CO_2e. Transportation to site net carbon contribution was 59,464 Kg CO_2e. Construction materials` net carbon emissions measured at 664,605 Kg CO_2e. Operating carbon emissions (represented with letters B1-B7 in graph below) measured at 1,616,818 Kg CO_2e. Energy use net carbon emissions were estimated at 1,359,037 Kg CO_2e. Lastly, end of life carbon emissions (represented with letters C-D) in graph below) were 52,409 Kg CO_2e. LCA Results show concrete, glazing, and steel as the most contributing materials of cradle to grave net carbon. Concrete emissions measured at 662 tons Kg CO_2e. Glazing emissions were 2.5 Kg CO_2e. Steel was estimated around 0.62 Kg CO_2e. Nonetheless, energy use generated the largest amount of net carbon over the life of the building at 55% of total emissions, followed by materials at 27%, and water use at 11% ((Figure 155). Similarly, electricity use accounted for 60% of net carbon emissions prior to PV integration and offsets (Figure 156).

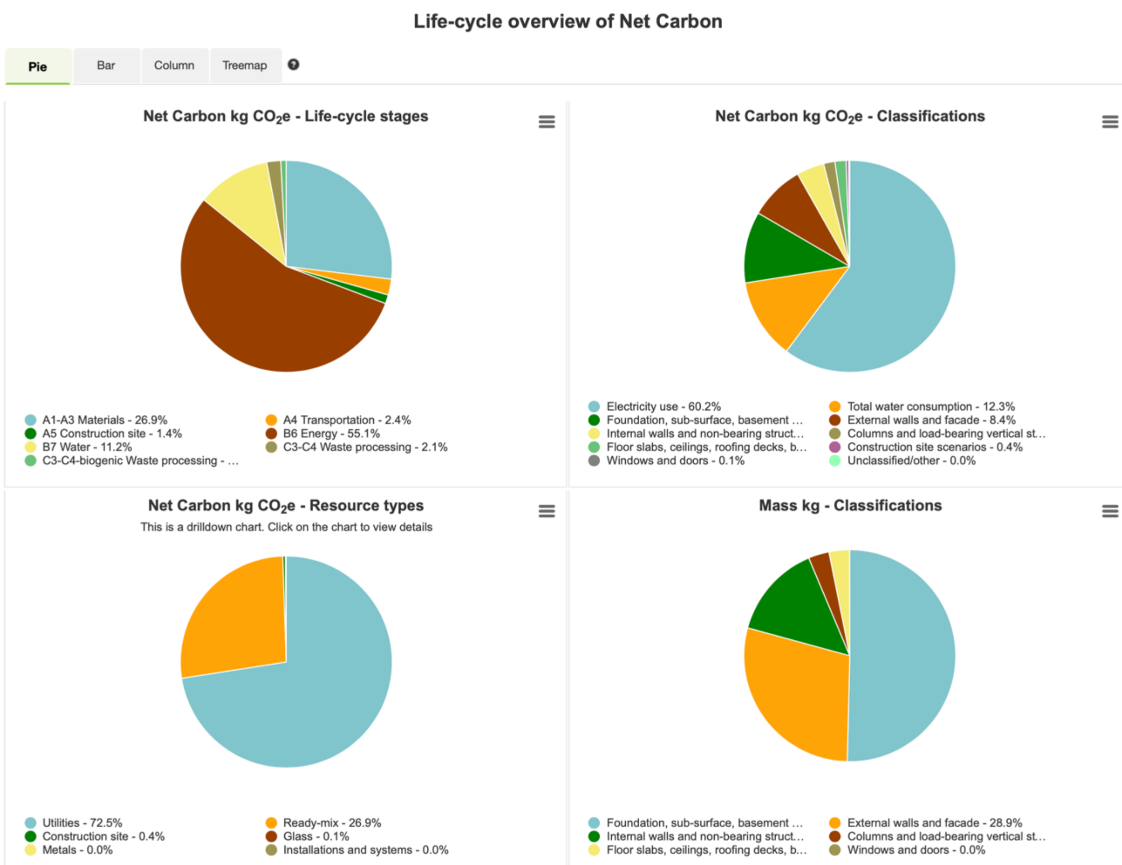

Figure 155. LCA charts showing Life-Cycle overview on the Building's Net Carbon Emissions

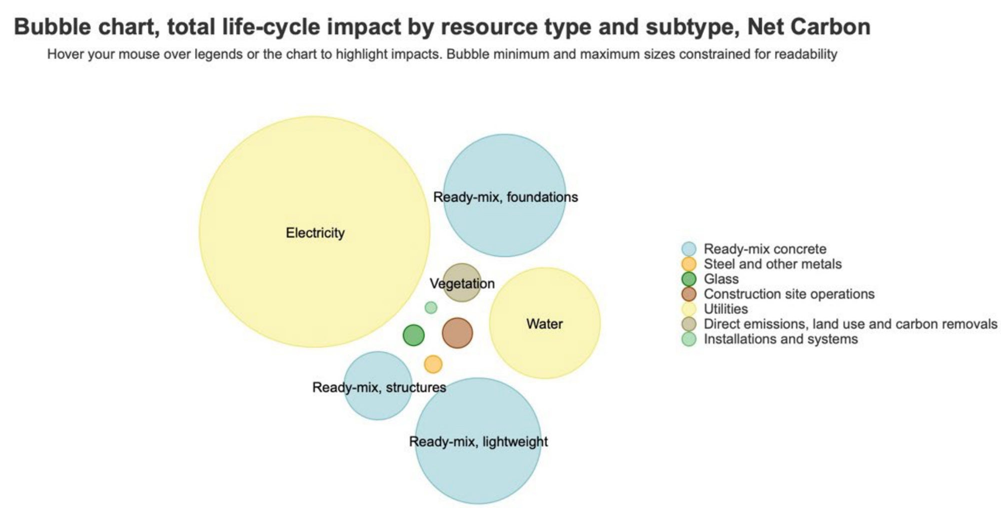

Figure 156. Bubble chart depicting total Life-Cycle net carbon impact by resource type and subtype

Construction materials were the primary contributor to embodied carbon by life-cycle stage, followed by transportation to and from site and end of life phase (Figure 157). When assessing the impact of structure on embodied carbon, foundations and substructure, and vertical structure and façade elements were the main drivers at 45% and 49% respectively.

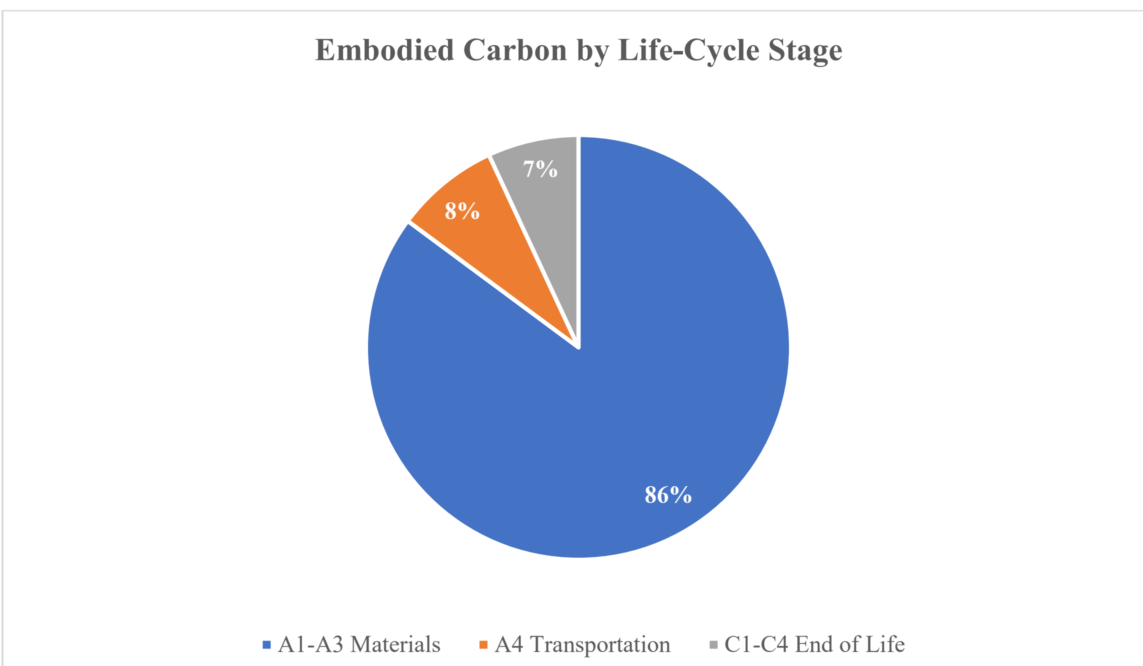

Figure 157. Embodied carbon by *Life-Cycle stages*

LCA Results from the Net Zero optimization run showed the building's total net carbon emissions at 2,256,714 Kg CO_2e, an 83% reduction from the baseline's 13,400,816 Kg CO_2e, driven primarily by the significant reductions in energy consumption and energy use intensity (Figures 158 & 159).

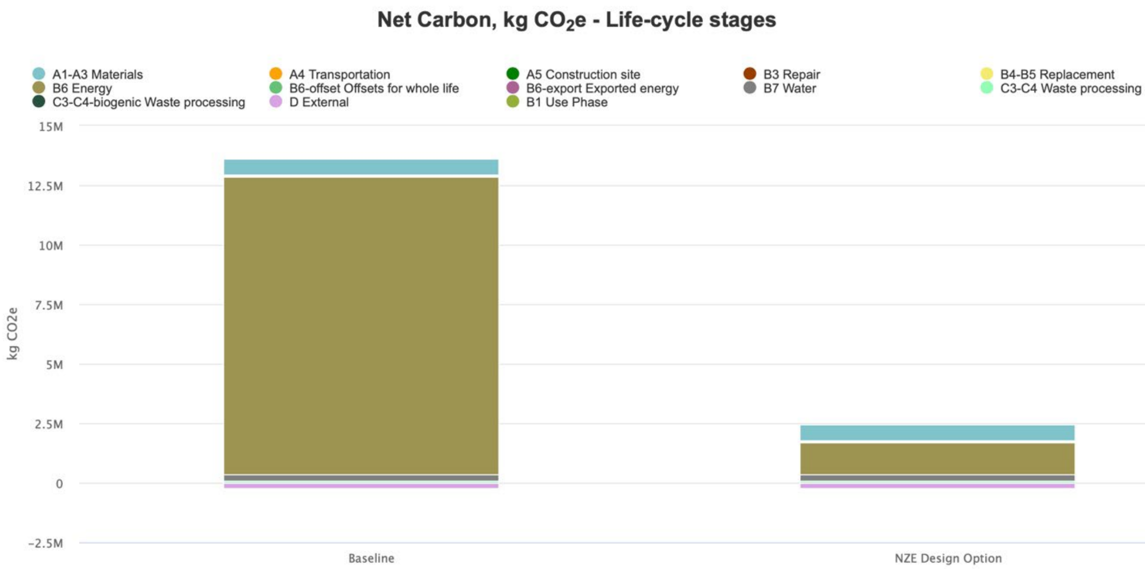

Figure 158. Net Carbon by *Life-Cycle stages* comparison chart between baseline and NZE runs

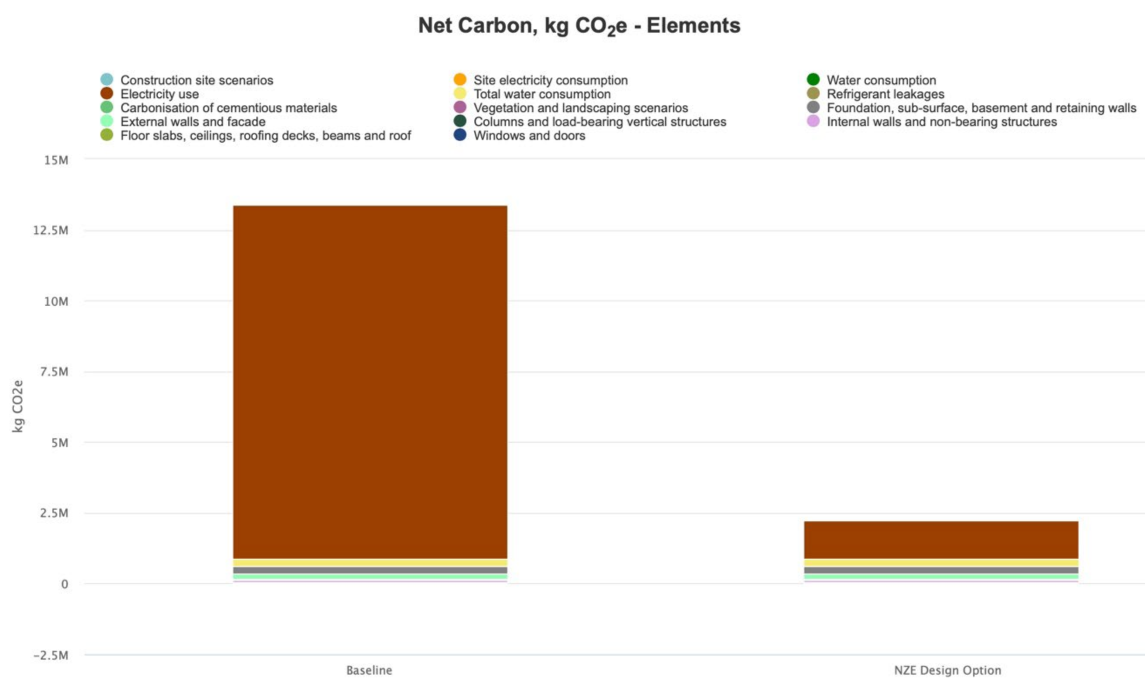

Figure 159. Net Carbon by *Elements* comparison chart between baseline and NZE runs

LCA findings showed a 7% increase in total embodied carbon (EC) intensity per unit area from the baseline to the NZE run (Figure 160). EC intensity is defined as the amount of released carbon by weight per unit of energy consumed per area (m^2). Nonetheless, the NZE's total operating carbon use intensity (CUI) was 100% less than the baseline, due to the drastic reductions in energy consumption and PV offsets; hence, offsetting any increases in the building's total EC intensity over its life cycle (Figure 161). Operational carbon is defined as the amount of carbon emitted during the building's operational in-use phase, which accounts for approximately 28% of global greenhouse gas emissions. As such, the NZEB run generated significant reductions in its carbon footprint due to the substantial decreases in the building's total EUI. Global warming potential (GWP) saving opportunities of the NZEB run are reflected in the Sankey diagram below (Figure 162).

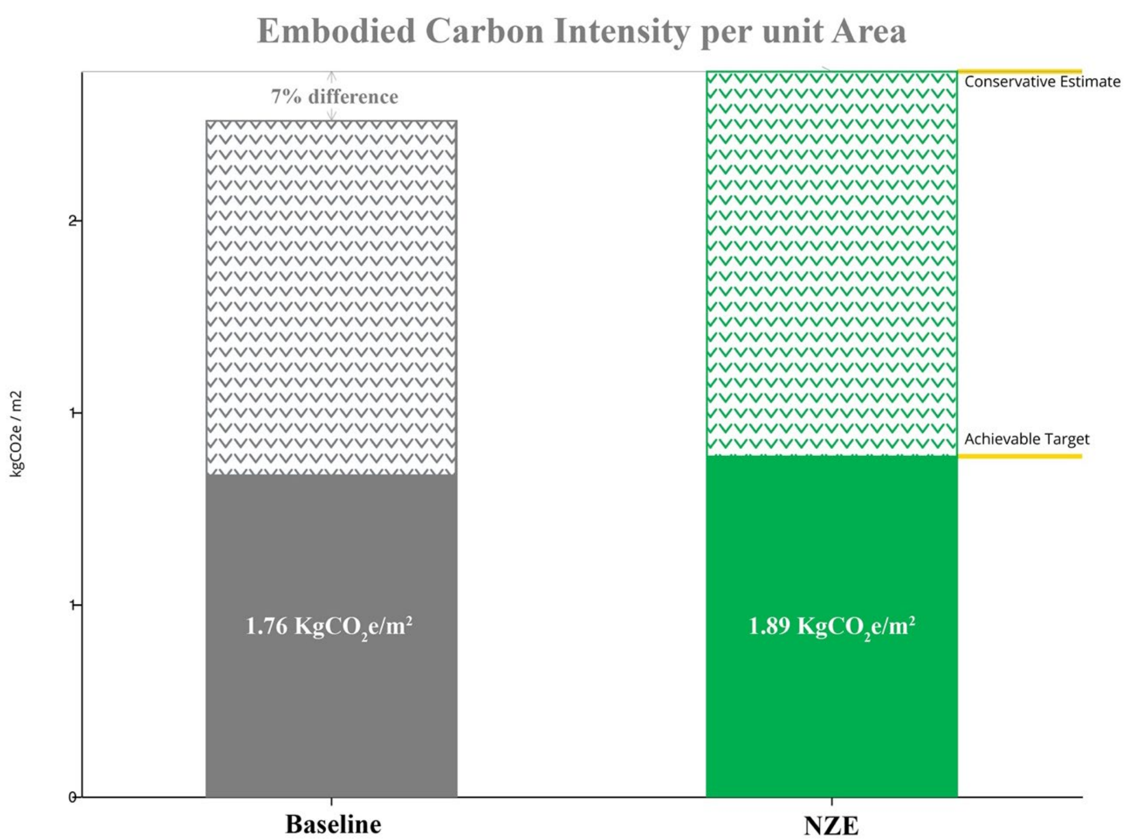

Figure 160. Comparison chart of the building's embodied carbon intensity (EC)

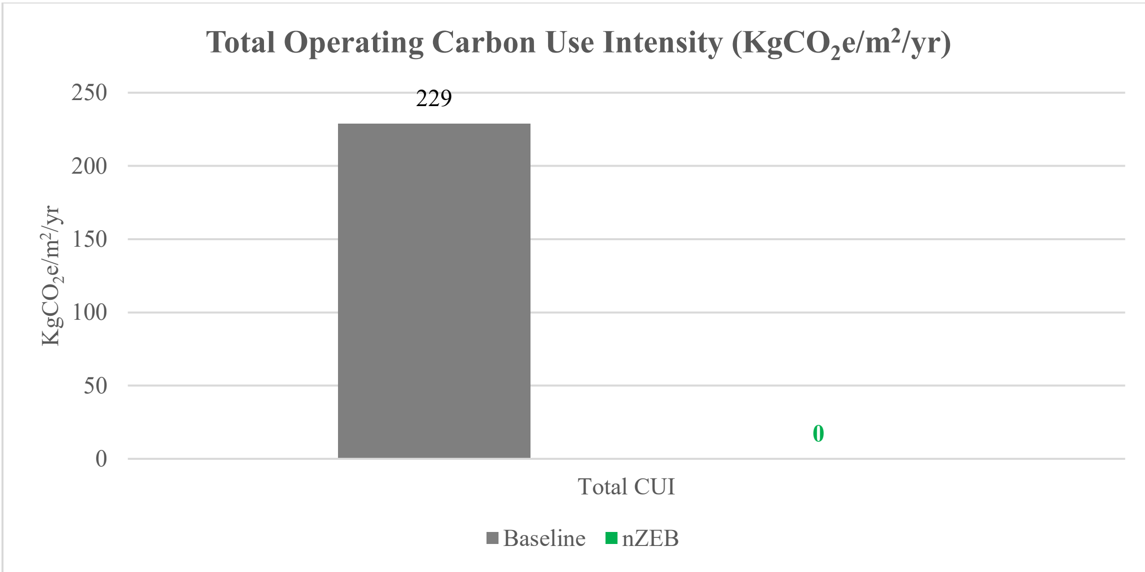

Figure 161. Comparison chart of the building's total operating carbon use intensity (CUI)

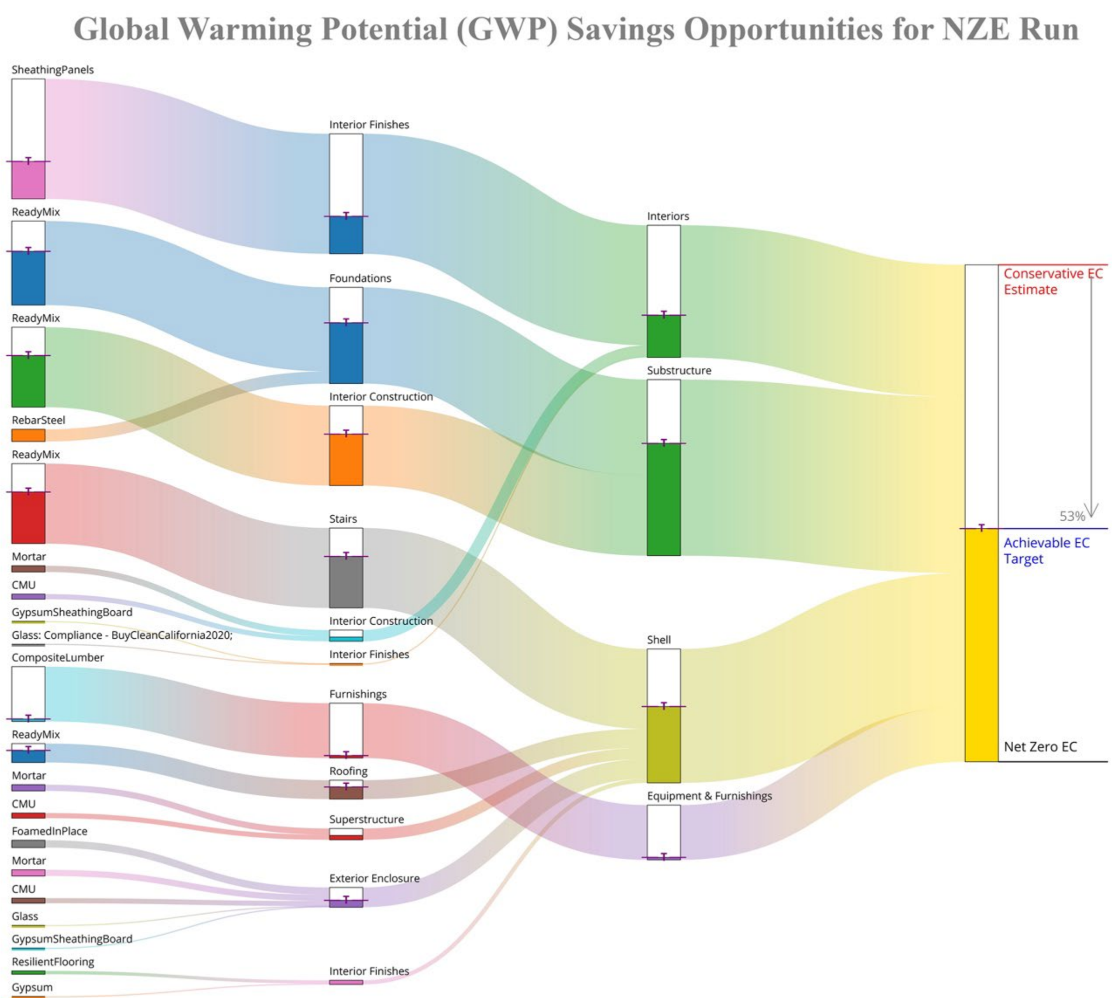

Figure 162. Global warming potential (GWP) saving opportunities of the NZE run

Chapter 9: Conclusion

Summary

Lebanon has been suffering from unreliable power supply since the civil war ended in 1990. Rolling blackouts are a normal part of life in Lebanese households. However, the ongoing two-year economic crisis have made matters worse. As a result, chronic blackouts have plagued the country during the past year and with no end in sight. Lebanese households have been forced to adjust to life without reliable electricity, due to the government's failure securing fuel oil because of the ongoing economic crisis. As a result, publicly provided electricity has been limited to 1 to 2 hours per day, forcing Lebanese to rely on privately-owned diesel generators for coverage of the remaining 22 to 23 hours, albeit at drastically much higher electricity rates and costs. Shortages in imports coupled with high demand have led to a severe scarcity in fuel supply, forcing the government to reduce subsidies on diesel fuel in the hopes of alleviating the problem. However, the move caused a fuel black market exacerbating fuel prices significantly and resulting in a four-fold price surge. Lebanese households have seen their private generation electrical bill increase dramatically reaching 8,500 Lebanese Pounds (LBP) per KWh (40 cents per KWh) at an average cost of 2,500,000 LBP ($200-375 in today's currency exchange market) a month for basic and minimum usage to just keep the lights on. The massive hyperinflation gripping the nation has caused a 20-fold increase in most household items and day-to-day products, while salaries and monthly incomes have remained stagnate. This have had a dramatic and devastating impact on low to middle income households that barely make on average around 2,280,000 LBP per month ($125-150 in today's currency exchange market). A family's entire monthly income is wiped out by utility cost, specifically private generation electrical bills.

Buildings have substantial impacts on energy consumption, the environment, and overall comfort and well-being of occupants. Increasing energy use associated with residential structures is a growing problem. Air pollution in Lebanon is a major concern to citizens and have become a major concern to public health. The World Health Organization (WHO) estimates place Lebanon's air pollution levels beyond all international standards. It's estimated that a 100% of the population is exposed to pollution levels above the WHO guidelines. To that end, the Lebanese building sector is a major consumer of energy and one of the primary drivers of air pollution in the country. The Lebanese building industry consumes around 45 to 75% of total generated electricity, most of which is produced in antiquated power plants using petroleum fuel oil as the primary source. Hence, the residential building sector is a significant driver of energy and electricity use patterns in the country. The residential sector, mostly multi-family apartment buildings, is a major contributor to air pollution, accounting for approximately 30-45% of total energy end-use consumption in Lebanon. Nevertheless, energy conservation measures (ECM) have not been widely adopted in Lebanon's residential building industry. Consequently, the country's residential green construction sector has lagged. Weak legislative and institutional frameworks, lack of enforcement mechanisms, absence of green construction legislation, subsidies of energy prices, and absence of an enforceable national energy strategy have all contributed to the minimal adoption of energy efficiency measures and policies in the residential building sector. Research addressing energy performance in Lebanese apartment buildings has been deficient, especially as it relates to zero energy metrics. To address these deficiencies, this study investigated the impact of various architectural upgrades on overall performance in a typical Lebanese residential apartment building. The main objective of this research was to develop and generate optimal architectural guidelines for the design of high-performance NZE apartment buildings in Lebanon, to reduce the impacts of energy use and associated emissions and air pollutants as well as provide Lebanese households resiliency and autonomy.

The Lebanese population is highly urbanized, with an estimated 90% living in cities. Most citizens live in standard residential blocks. The houses are typically apartments in multi-story buildings. Standard apartment buildings accounted for approximately 70% of the residential market in 2012 (BankMed, 2014). Home sizes in Lebanon are amongst the highest when compared to regional counterparts. Similarly, household size in Lebanon is amongst the highest as well. Lebanese households typically consume a large amount of electricity in comparison to other countries (Figure 163), attributed mainly to socio-cultural behavioral habits. Electricity consumption per Lebanese household increased over 4% per year between 2000 and 2010 primarily due to growth in equipment usage (TV, refrigerators, ovens, air conditioning, ICT, water heaters, etc.) (MEDENER, 2014). Most of the energy use spikes in Lebanese households could be attributed to the following four end uses and societal norms: home cooking, watching TV, lighting, and air conditioning. Lebanese cultural norms show that families spend more than 65% of the day in the kitchen preparing meals, cooking, and watching TV. Refrigerators, TVs, washing machines, and ovens are usually the most used home appliances. Studies have shown a 20-30% energy saving potential when such equipment is replaced with energy-efficient appliances (Omar, 2020). Nonetheless, most appliances and equipment used in Lebanese households are antiquated and inefficient. Residential Energy Use Intensity in Lebanon is relatively high compared to regional counterparts, especially countries with similar climate (Figure 164). Home and household sizes are probably contributing factors, in addition to lack of thermal insulation as well as cultural behavioral patterns and practices. However, lack of energy conservation measures and inefficient appliances are also major factors in increasing residential energy. As a result, the residential sector in Lebanon consumes approximately 30-50% of the total generated electricity (compared to 25% in regional Mediterranean countries), constituting the largest amount of energy end-use consumption, and hence a significant driver of air pollution in the country. To that end, electrical residential demand increased from 3,080 GWh in 2009 to 5,750 GWh in 2014 (LCEC, 2018). The average Lebanese apartment building has an EUI between 135-220 KWh/m^2/yr. An average EUI of 184 kWh/m^2/yr was generated based on existing data for purpose of the study. Residential electricity demand is largely composed of heating, cooling, equipment, lighting, and domestic hot water. Most residential buildings are not properly insulated, and in some instance, not insulated at all (Yathreb, 2016). This is directly attributable to the fact that none of the thermal insulation standards were ever adopted and remain primarily voluntary. Furthermore, most green energy and sustainable construction initiatives are voluntary in nature and lack meaningful enforcement mechanisms (Awwad E. K., 2012). Consequently, energy efficiency measures and upgrades aren't widely adopted in the residential sector. Efforts to bring to bear energy efficiency investments in Lebanon have been challenging and slow at best, especially in the residential building market. systemic, economic, social, political, and cost barriers are some of the fundamental elements hindering the growth and adoption of robust energy conservation measures within the

Lebanese residential sector. The fundamental premise of this research is to bring NZE practices to the forefront by providing an easy-to-follow performance-based roadmap, to provide Lebanese households resiliency and immunity from future potential crises.

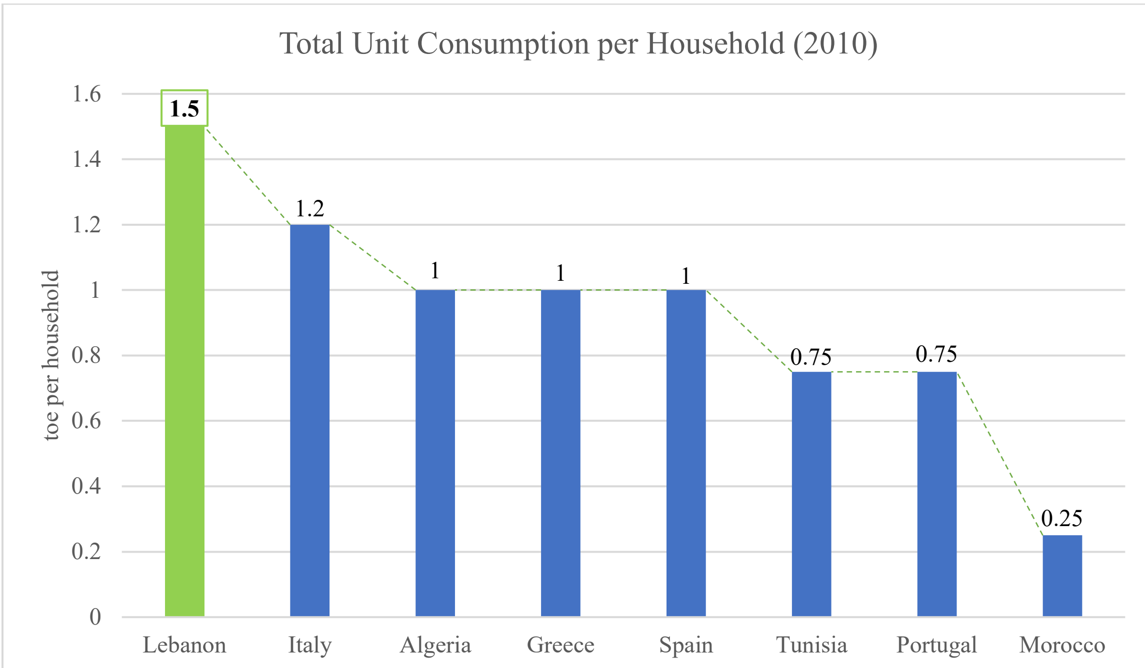

Figure 163. Total unit consumption per household comparison chart *(MEDENER, 2017)*

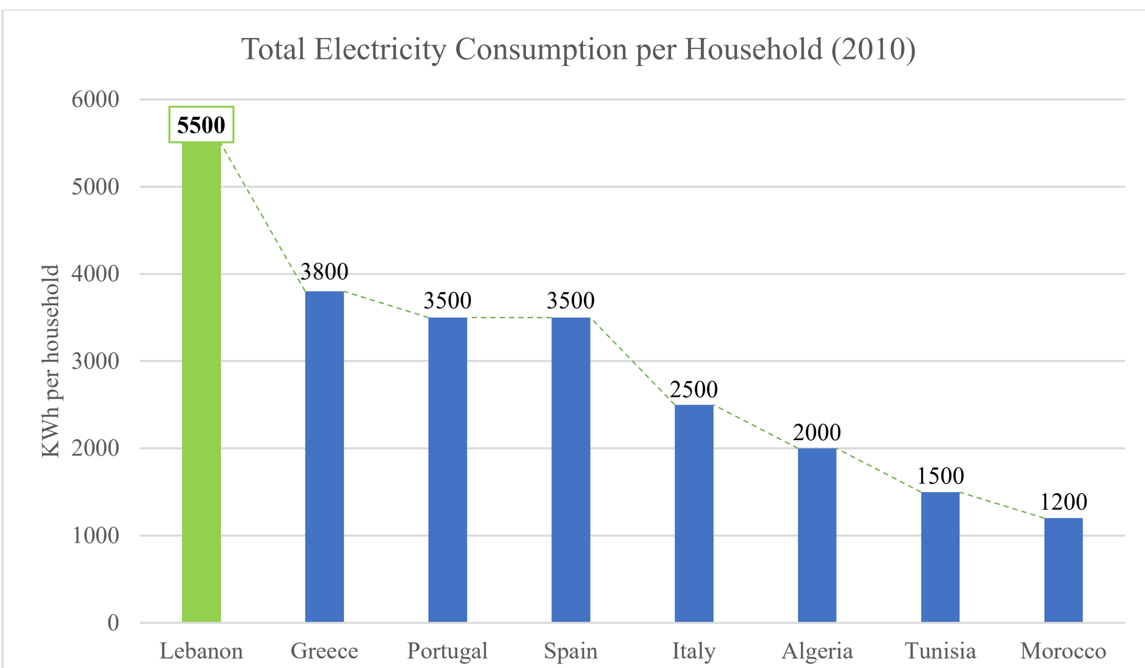

Figure 164. Total electricity consumption per household comparison chart *(MEDENER, 2017)*

To address the research questions, hypothesis, gaps, and study's fundamental premise, the following sequential methodology was employed: First, a comprehensive review and examination of regulatory barriers and technical data was conducted; second, data from surveys were collected and analyzed to gauge respondents` perceptions of energy efficiency and NZE practices; third, an extensive quantitative iterative parametric energy modeling and simulation approach, using the Cove Tool as the primary energy simulation engine, was employed to assess and analyze various building performance metrics. Lastly, comprehensive optimal NZEB guidelines and practices for multi-family apartment buildings in Lebanon were recommended based on the simulation findings. To that end the study utilized an incremental multi-stage modeling and simulation approach. Individual design configurations and buildings system variables, including both passive and active strategies, were evaluated in the first modeling stage, followed by a building optimization stage examining a combination of optimal strategies (passive + active + design) derived from the first stage. Lastly, NZE modeling optimization, including on-site renewable energy generation, was initiated to evaluate the impact on building performance.

Findings and Contributions

Findings

Residential structures are primarily skin-load dominated buildings; whereby thermal loads are significantly driven by exterior climatic conditions. Hence, the building envelope and HVAC systems are critical components of the overall thermal boundary. Heat gains and losses are significantly impacted by a structure's thermal envelope specifications. Studies have shown building envelope thermal load fluctuations ranging between 15% and

35% in a code-built single-family home (Bichiou & Krarti, 2011). Simulation results revealed similar trends in the modeled building. Energy demand was heavily driven by the building's overall surface area, footprint, and envelope typology. Furthermore, analysis of the individually simulated building design and systems parameters revealed that energy loads were predominantly driven by space conditioning demands as well as lighting and equipment loads. Similarly, data analysis of the various optimized iterations exhibited a noteworthy trend as it relates to overall energy performance, showing the above-mentioned loads as the primary drivers of energy consumption in the building. Hence, passive strategies were essential in reducing overall building energy loads. The application of passive design strategies combined, reduced the building's energy loads and total consumption by approximately 20% (Figure 165). Active strategies were employed next to optimize performance. The cumulative application of active design strategies (without solar PV/DHW) reduced energy loads and energy consumption by approximately 36% (Figure 166). Combined, passive and active strategies yielded 56% reduction in energy consumption compared to the modeled baseline scenario. Nonetheless, HVAC and envelope insulation upgrades ranked highest in energy use savings potential (Figure 167).

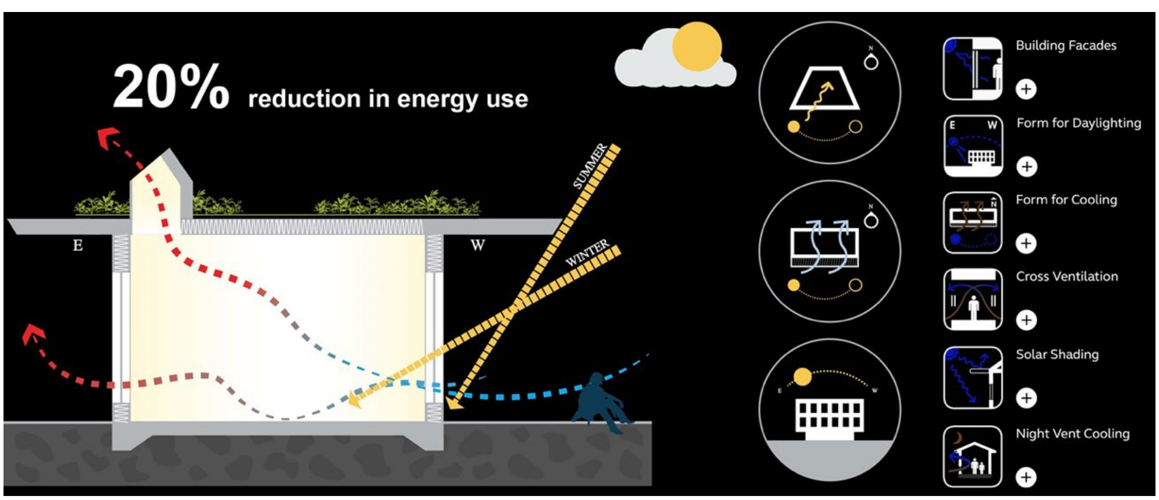

Figure 165. Section diagram illustrating passive strategies and their impact (courtesy of climatescout)

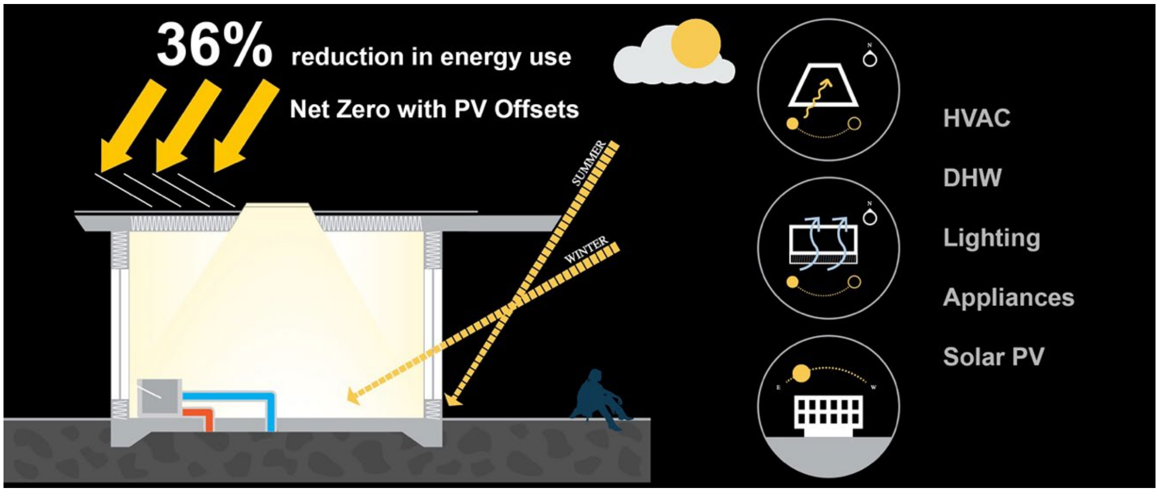

Figure 166. Section diagram illustrating active strategies and their impact (courtesy of climatescout)

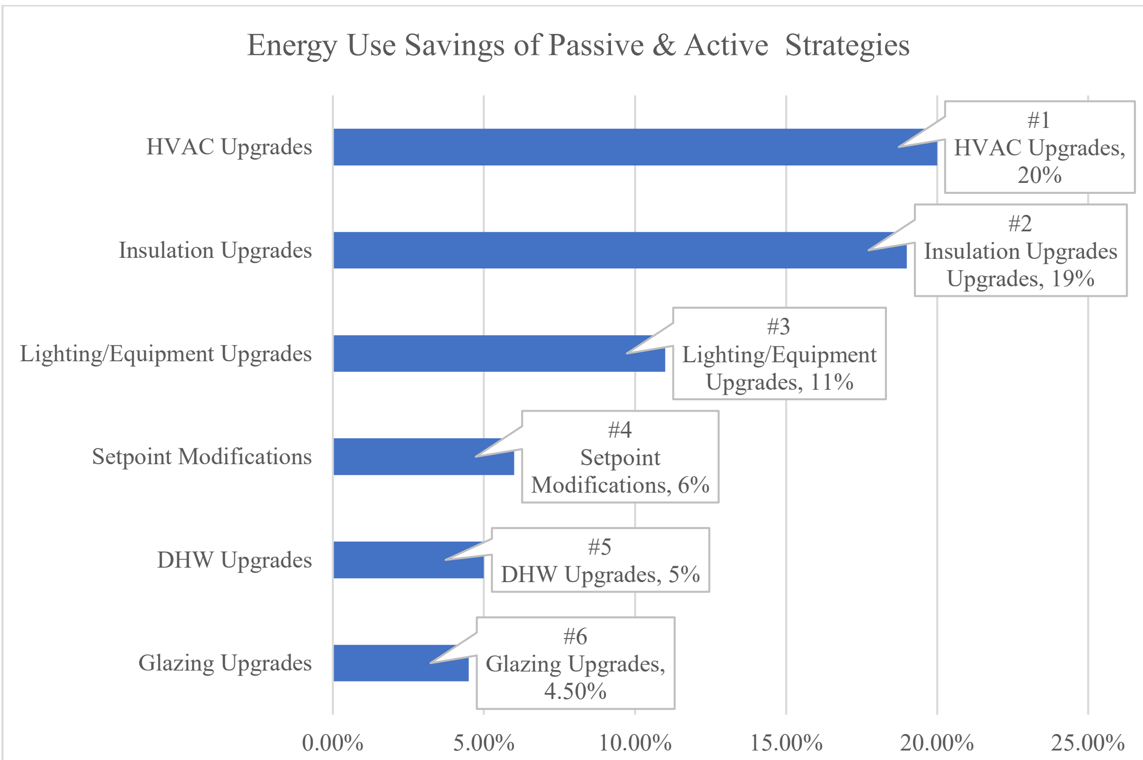

Figure 167. Energy use savings potential ranking of various passive and active strategies

The above-mentioned rankings are based on the parameters set for this project, primarily encompassing EUI impacts and overall energy efficiency performance. However, those rankings would look different if cost and feasibility parameters were the main driving factors. As such, lighting and equipment upgrades would be ranked first.

Results from the parametric simulation analysis revealed building system upgrades (passive + active) having a greater impact on energy consumption than building design changes. To that end, individual building design variations yielded energy use reductions between 0.3% and 6% compared to the baseline. On the other hand, individual building system modifications generated EUI reductions between 4% and 20%. Building system improvements such as envelope insulation and HVAC upgrades were significant drivers of energy reductions in the multi-family apartment building, yielding 18 to 20% energy use reductions respectively. The combination of a thermally insulated building envelope with a high-efficiency HVAC system provided an exceptionally high-performance building. The increased levels of insulation enhanced the envelope's overall thermal resistance, drastically reducing infiltration and leakage rates. Thermal conditions were further improved via the high efficiency HVAC system. The ground source heat pump's high COP provided an optimal thermal environment, ultimately driving energy loads substantially lower than the baseline. Collectively, the increased levels of thermal resistance throughout the building envelope coupled with high-efficiency HVAC systems produced a super-efficient thermal structure. Lighting/equipment upgrades and space conditioning setpoint modifications were the next most optimal set of variables, besides the insulated envelope and high-performance HVAC, reducing energy consumption by 11 and 6% respectively. Cumulatively, the optimized combination of building design and system variables (compact footprint, insulated envelope, high-performance HVAC, Solar DHW, high-performance glazing, efficient lighting, and efficient appliances) generated a 56% reduction in energy consumption over the modeled and existing baseline, and 32% below the 2030 baseline. The optimized building yielded an EUI of 84 kWh/m^2/yr compared to the baseline EUI of 191 kWh/m^2/yr. Moreover, it generated 60% less carbon dioxide emissions (35.5 Tonne/CO_2e/yr) than the modeled baseline (92.5 Tonne/CO_2e/yr), and 40% less than the 2030 baseline (60 Tonne/CO_2e/yr). In aggregate, the optimized building reduced energy consumption over the baseline by more than half, paving the way to a Net Zero-Ready building. The afore mentioned parameters were adopted for NZE optimization and analysis. Thereafter, Photovoltaic on-site energy generation was integrated into the building to transition into a Net Zero Energy Status. Simulation results from the Net Zero Energy building optimization run yielded a Net EUI of 0 kWh/m^2/yr, a 100% reduction in net energy consumption over the baseline (Figure 168). The deployment of the PV system accounted for 100% of total energy consumption, offsetting 84 kWh/m^2/yr of the building's overall energy use intensity and generating approximately 134,000 kWh of on-site electricity annually. Moreover, simulation results of the NZE building optimization revealed a 100% reduction in CO_2 emissions from the baseline, yielding 0 Tonne CO_2e/yr. As a result of the significant energy reductions, the building's total annual energy and electricity costs were cut by 100% compared to the baseline.

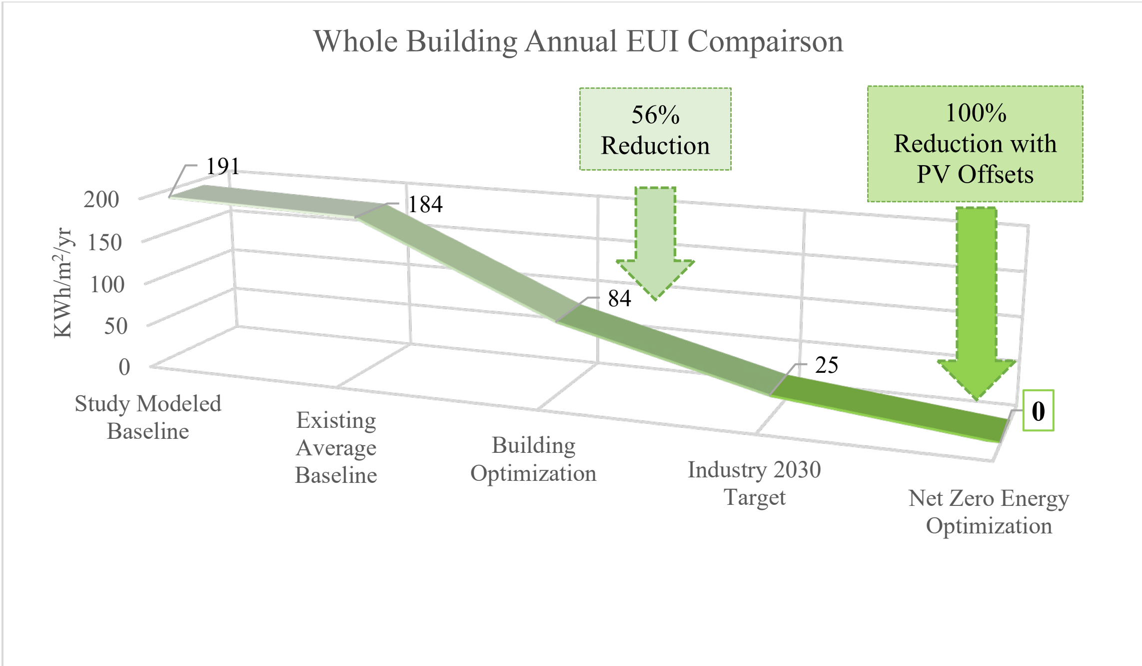

Figure 168. EUI comparison chart showing the evolution of energy reduction

Based on the generated results of the building optimization simulation, the initial hypothesis, predicting the most optimal architectural indicators to include insulated thermal envelope, high-efficiency HVAC & DHW systems, high-performance glazing, high-efficiency lighting and equipment, compact footprint, and south-facing shading systems, was mostly accepted albeit with one caveat. The initial hypothesis predicted south-facing shading systems as one of the optimal energy performance indicators. However, simulation results revealed less than a 1% reduction in energy consumption over the baseline when applying such a strategy. This is probably due to the permissible recommended percentages of WWR within the façade composition, hence, reducing the overall efficacy of shading systems. Still, it’s considered an effective contextual passive strategy to minimize heat gains as well as enhance thermal comfort. All other hypothesized parameters were successfully predicted. These general parameters should provide the foundation for NZE best-practice guidelines (Figure 169).

Figure 169. NZE targeted list of architectural indicators including passive and active strategies

The following are key findings of the study:

- Deployment of Passive strategies first (solar, ventilation, daylighting, insulation, shading, etc.) is essential to reducing energy loads and transitioning the building to a net-ready zero energy structure.
- The application of passive design strategies combined reduced energy loads and total energy consumption by approximately 20%.
- The application of active design strategies combined (without PV), reduced energy loads and total energy consumption by approximately 36%.
- Compact footprint and massing coupled with optimum WWR (15-22%) and shading systems are essential to ensuring optimal energy performance.
- Minimize amount of glazing on the colder sides of the building (north and east facades), while optimizing percentages and placement on the south and west with appropriate shading systems.
- Building systems upgrades yielded larger energy savings than building design modifications.
- Building envelope upgrades (insulation and thermal mass) generated 18% energy reductions over the baseline.
- HVAC sand DHW systems upgrades (heat pump system or equivalent in performance) yielded 26% reduction in energy use over the baseline.

- Lighting and equipment upgrades generated 11% energy reductions over the baseline.
- Space-conditioning setpoint variations reduced energy consumption by 6%.
- Glazing upgrades (double pare or triple pane) reduced energy use by 4%.
- Collectively, building design + systems optimization upgrades yielded a 56% reduction in energy consumption over the baseline.
- Lastly, building NZE optimization (PV integration) yielded 100% reduction in energy consumption over the baseline (Net EUI of 0 $kWh/m^2/yr$), a 100% reduction in CO_2 emissions at 0 Tonne CO_2e/yr, and an 100% reduction in life cycle operating carbon use intensity over the baseline.

Contributions

Lebanon has been grappling with mounting crises over the past decade and intensely during the past two years. The country has been suffering from 3 prevalent crises, political, economic, and social. Lebanon's massive hyperinflation has led to social turmoil and a rise in poverty levels. The country's severe power outages and gas shortages coupled with rising fuel prices, has further exacerbated socio-economic conditions for the low to middle income sectors of the population. Lebanese households on average received no more than 2 hours of public-generated electricity per day in 2021, hence, forcing households to rely on the very expensive and unreliable private generation market. The research aimed to provide Lebanese people a path towards resiliency and immunity from potential and inevitable future crises. The research's fundamental premise is to affect transformative change from the bottom up to provide the Lebanese people resilience from political crises, economic independence, social equity, and safety. To that end, the research has four primary objectives, outlined in the chart below.

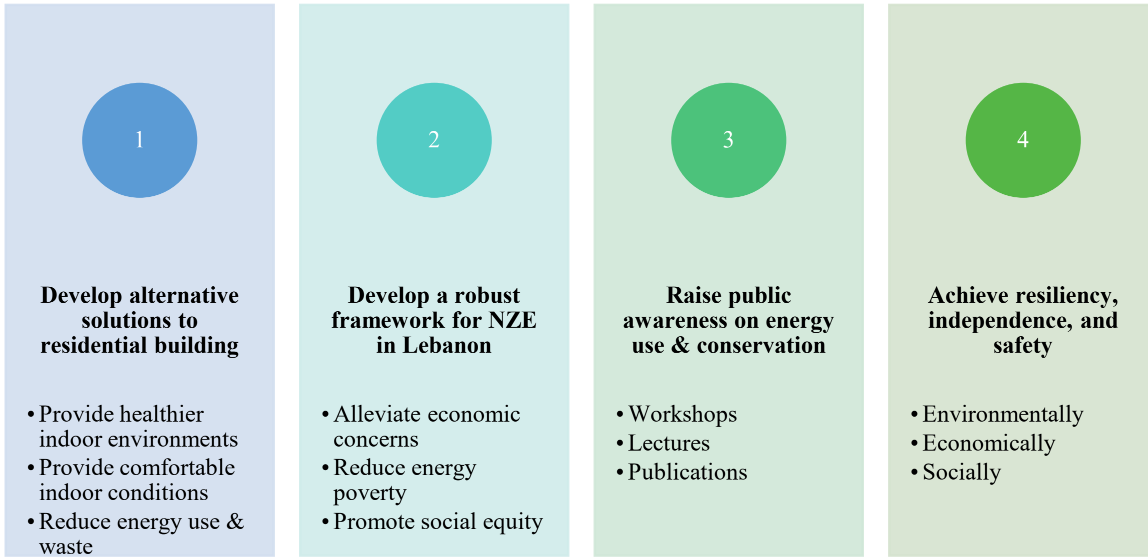

Figure 170. Chart highlighting the research's 4 primary objectives

To achieve those four main objectives, the research developed two primary deliverables. First, a set of comprehensive guidelines for NZE apartment buildings in Lebanon, encompassing design parameters, passive practices, and active strategies. These guidelines were generated based on the extensive literature research, survey analysis, and parametric simulation evaluation. Second, the research developed a preliminary framework for an informational mobile app offering best practices and strategies to inform and educate stakeholders, especially homeowners. The two deliverables are primarily intended to inform and educate Lebanese stakeholders on the approaches, methodologies, benefits, and impacts of a NZEB approach within the residential sector.

NZEB Guidelines

The research developed a set of comprehensive guidelines for Net Zero Energy apartment buildings in Lebanon, encompassing design parameters, passive practices, and active strategies. The guidelines included general Net Zero Energy Building parameters, passive building-design best practices, active building-systems best practices, targeted performance-based strategies, and existing buildings recommendations. The guidelines were generated based on the extensive literature research, case studies analyses, survey evaluation, and the parametric energy simulation investigation. The guidelines are contextual in nature and take into consideration local climate and context. All guidelines are performance-driven, tailored to give stakeholders and decision makers utmost flexibility in selecting applicable and appropriate project-specific strategies. The first set of guidelines encompassed a holistic sequential framework and methodology for effective and optimal NZE approaches (Figure 171).

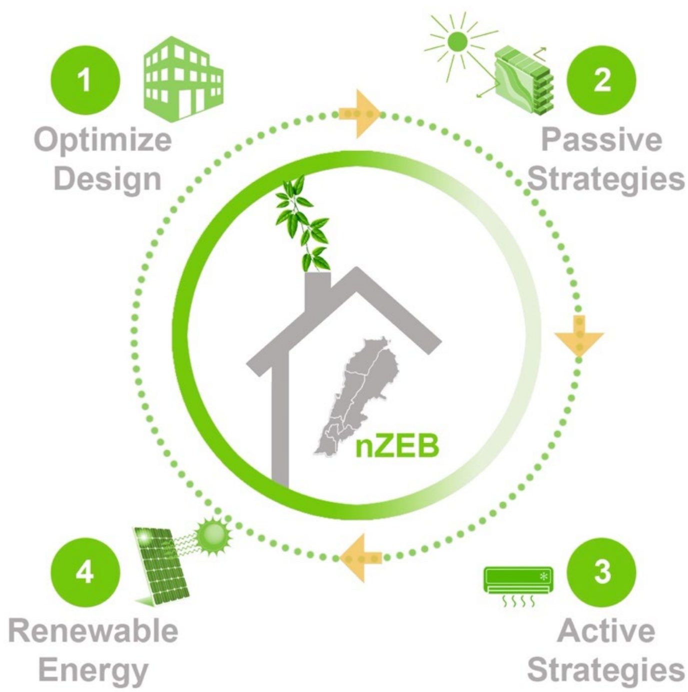

Figure 171. Sequential framework for an optimal NZE approach

The second set of comprehensive guidelines encompassed Net Zero Energy ***General best-practices*** for Lebanese multi-family apartment buildings (Figure 172).

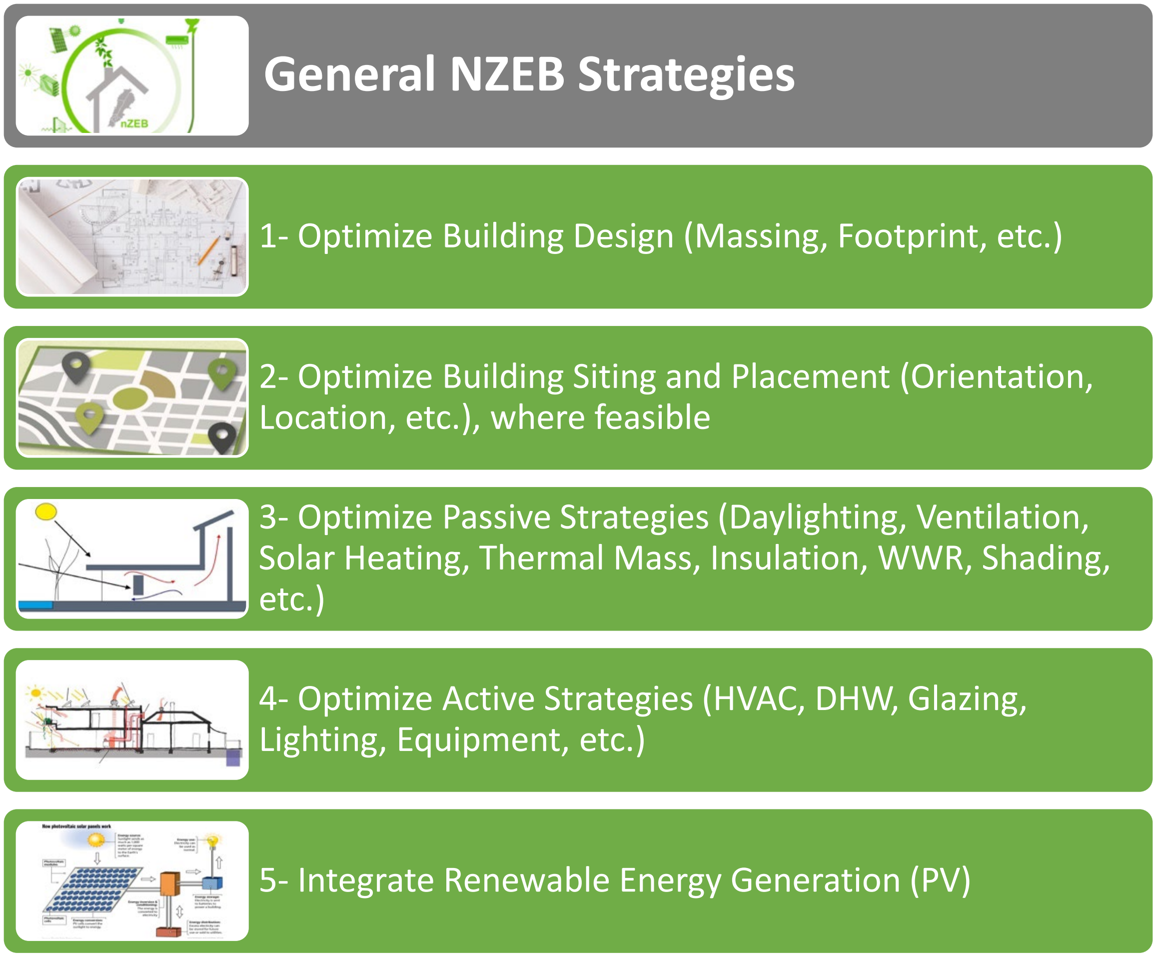

Figure 172. General comprehensive guidelines for NZE apartment buildings

The third set of comprehensive guidelines encompassed Net Zero Energy ***Passive Building-Design best-practices*** for Lebanese multi-family apartment buildings (Figure 173). The guidelines focused primarily on passive building design strategies and practices that requires no active systems deployment and hence, doesn't' require any operational energy. Given the mild Mediterranean climate of Lebanon (especially climate zone 1), characterized with moderate temperatures and an abundance of sunlight, passive cooling and solar heating strategies are paramount to reducing the building's overall energy loads.

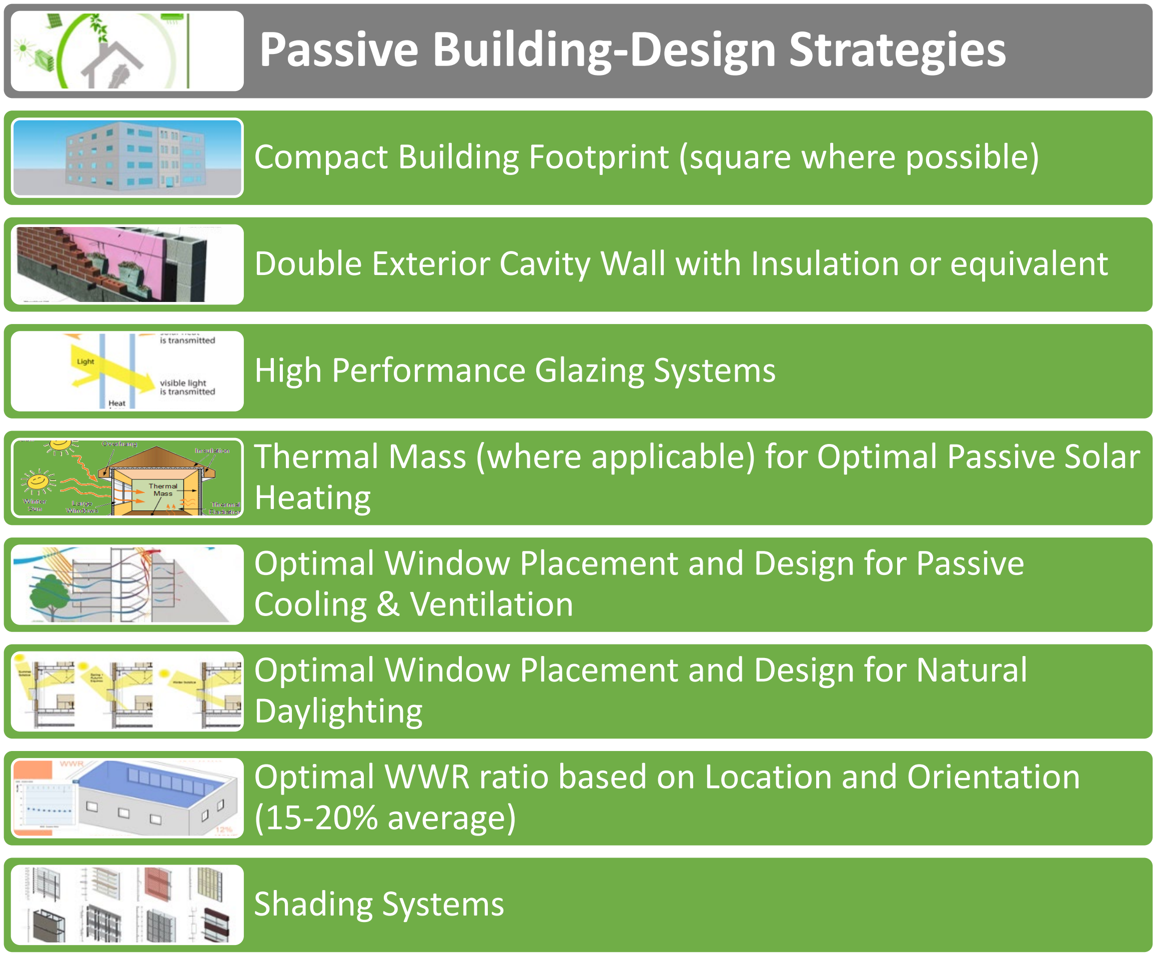

Figure 173. Building-design passive guidelines for NZE apartment buildings

The fourth set of comprehensive guidelines encompassed Net Zero Energy ***Active Building-Systems best-practices*** for Lebanese multi-family apartment buildings (Figure 174). The guidelines encompassed active building systems strategies, which by design uses less energy, and hence reduces overall operational energy loads and consumption. The strategies focused on mechanical systems, lighting, and equipment. The initial deployment of passive strategies yielded significant reductions in the building's energy loads, paving the way to smaller mechanical systems and equipment. Moreover, the utilization of passive strategies for heating, cooling, and lighting generated sizable reductions in energy consumption, and hence decreased the size and scope for such active systems.

Figure 174. Building-systems active guidelines for NZE apartment buildings

The last set of comprehensive guidelines encompassed Net Zero Energy ***targeted performance-based strategies*** for Lebanese multi-family apartment buildings (Figure 175). The guidelines were generated based on the extensive parametric energy simulation analysis and examination. The strategies included both passive and active systems. These systems and strategies, combined, can yield 90-100% reductions in total energy consumption and annual energy costs. The recommended guidelines were chosen based on performance, availability, applicability, and prevalence within the Lebanese residential construction market. Green residential applications and approaches are limited in coverage within the Lebanese residential multi-family apartment sector. However, when available, the following strategies have been used and employed effectively.

Figure 175. Targeted performance-based guidelines for NZE apartment buildings

Net Zero Energy housing is a significant paradigm shift within the Lebanese residential construction sector. To affect such change on a large scale, investments in existing building stock are necessary and can't be ignored. It's paramount we address optimal methodologies and strategies to retrofit existing apartment buildings to enhance their performance and transition them to Zero Energy Ready buildings. To that end, an on-ground survey of 625 households in the town of Bishmizzine, a neighbouring town of Amioun (the primary location of the study), was conducted to assess the status of the existing building stock in terms of energy efficient features and overall thermal conditions. Most residences (single family homes and apartment buildings) didn’t have any significant energy efficient features outside of lighting, appliances and few applications of solar PV and hot water systems (5% of residences had PV systems). Most buildings were not insulated, didn’t have a high-performance HVAC and DHW systems, used antiquated appliances, and had single pane glazing systems. Accordingly, energy use and overall performance of most buildings in town were negatively impacted. The absence of energy conservation and efficiency measures is exacerbating household’s utility costs and thermal comfort levels. The following chart outlines the most optimal strategies for retrofitting existing buildings, prioritized based on ease of applicability and installation (cost, labor, scope, disruption, and structural changes).

Figure 176. Targeted NZE performance-based guidelines for existing residential buildings

It's important to also consider nearly net zero energy buildings (nZEB) as part of the comprehensive set of guidelines. While financial considerations and limitations might prohibit the full adoption and implementation of a net zero energy approach, a nZEB offers a viable alternative with tremendous benefits and impacts (Figure 177).

Figure 177. Targeted NZE performance-based guidelines for existing residential buildings

The recommended NZE building guidelines are meant to be holistic, not prescriptive. The intent is to contextualize each project's guidelines based on location and appropriate factors. The guidelines serve as a foundational platform that provides stakeholders a menu of items to consider based on feasibility, applicability, and impact. Nonetheless, these guidelines were generated based on broad literature research, survey analysis, and iterative parametric energy simulations. To validate the results, a focus group survey was conducted to assess the viability and legitimacy of the recommended guidelines. The survey was sent to 152 Lebanese respondents encompassing homeowners, students, and building professionals (Figure 178). Respondents were presented with the recommended guidelines and asked if they agree with them or not, and if they have other alternatives. Building professionals constituted the largest percentage of respondents. The survey's main objective was to gauge stakeholder's perceptions of the recommended NZE building guidelines to validate their efficacy and applicability in the Lebanese market. This contextual substantiation is vital to the success and viability of the study.

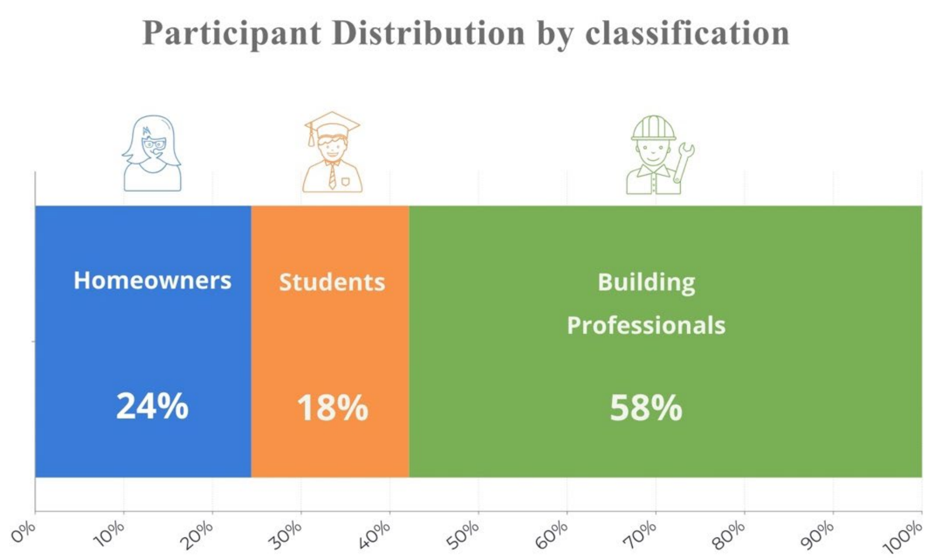

Figure 178. Percentage distribution of Lebanese focus group respondents by classification

97% of total respondents agreed with the recommended guidelines as applicable, viable, and optimal Net Zero Energy building strategies in the Lebanese residential market. 100% of homeowner and student respondents indicated their agreement with the recommended guidelines. More importantly, 95% of building professionals agreed with the suggested NZE building guidelines (Figure 179). These results strongly validate and re-enforce the viability of the NZE recommendations as optimal and feasible foundational guidelines to advance the concept of NZE residential buildings in Lebanon.

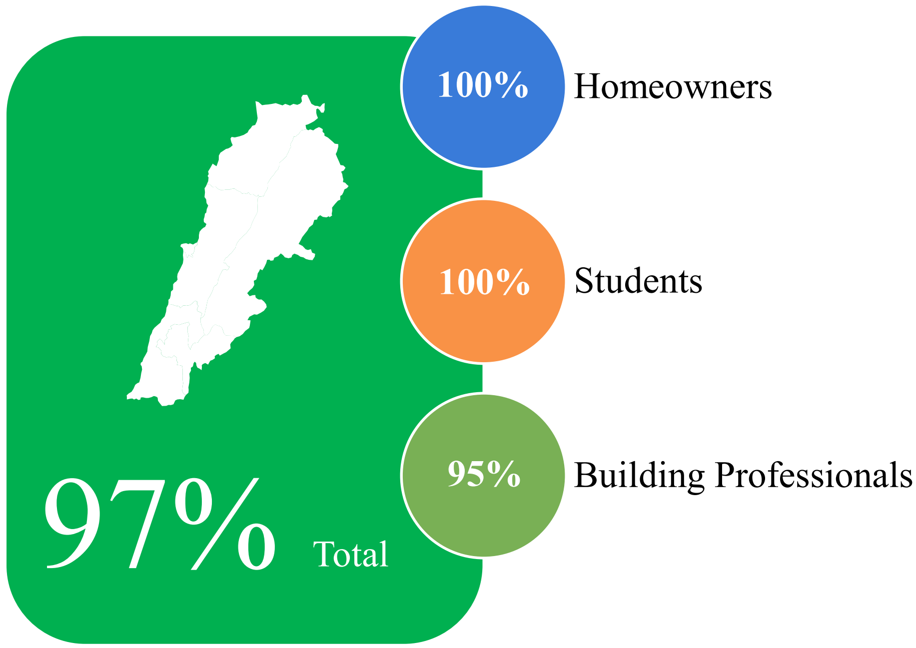

Figure 179. Percentage of respondents agreeing with recommended NZE guidelines

NZEB Mobile App

The research aims to provide an informational mobile app targeting energy reductions and conservation measures in Lebanese households specifically and regional homes in general. The free mobile app would be accessible on smart phones or tablet devices from the Apple app store and Google Play. The app would offer contextual climate and household-specific sustainable passive and active design recommendations. This is extremely important due to the rising global costs of energy and the difficulty in obtaining clean, affordable, and reliable electricity in locations such as Lebanon and several other locations. The app will help people utilize proven methods to reduce their energy use and potentially achieve net zero in some climates. A significant reduction in home energy consumption is an enormous asset to millions of people globally, especially those in developing countries such as Lebanon. Moreover, energy poverty and energy access are chronic symptoms usually and disproportionally afflicting low-income sectors. This proposed mobile app would provide low-income households a free and easily accessible tool to learn about easy-to-implement energy reduction measures and cost saving strategies that could mitigate their energy poverty and lessen their financial burdens. This app could also help families looking for a new home or in the process of designing and constructing a new home, make sound and targeted energy efficient decisions. Similarly, the app would provide simple-to-do guideline for retrofitting existing homes. Furthermore, this app would also help combat climate change and its impacts on our planet by making energy efficient solutions readily available to ordinary people. One of the research's primary objectives is educating and informing people on energy conservation and efficiency measures. This free resource, which would be readily accessible to anyone via a smart phone or device, would potentially reach 6.6 billion people worldwide according to Statista. To that end, the research developed a preliminary framework for an informational mobile app offering NZEB best practices and strategies to educate stakeholders, especially homeowners (Figure 180). A fully functional interactive App will be pursued post the research termination. Apps are ideal platforms to promote awareness of NZEB. They are also crucial components in educating stakeholders about residential energy efficiency and conservation measures. A 2019 study evaluating the efficacy of apps usage in promoting energy savings in the Netherlands concluded that feedback systems with direct feedback have shown to be successful in motivating households to adjust their energy use levels (Geelen, Mugge, Silvester, & Bulters, 2019). Another study has shown that mobile apps were effective in promoting household's energy consumption management and stimulating a robust energy efficiency culture and behavior among users (Hussain & Mkpojiogu, 2017). Most households in Lebanon lack access to real-time reliable information regarding energy use and efficiency. Furthermore, there's an absence of readily available information on energy conservation and efficiency. Hence, such an endeavor might prove instrumental in advocating and promoting sustainability-focused practices, including NZEBs.

Figure 180. Framework for an informational NZEB mobile App

Benefits and Impacts

This study seeks to advance the knowledge of energy efficient practices and conservation measures within the Lebanese residential market. Its main objective is the proliferation of more sustainable, resilient, and energy positive buildings. The research aims to promote Net Zero Energy Buildings as a viable and sustainable building approach to combat energy poverty, social equity, economic destress, and environmental degradation in Lebanon. Energy poverty is usually caused by rising energy prices, energy inefficient buildings, and low-income status. This research's most critical contribution is providing Lebanese households a viable and achievable path towards reducing and eliminating energy poverty. The study is anticipated to yield multiple benefits, locally and nationally. The research will advance residential energy efficiency trends, which will inevitably lead to significant reductions in residential energy consumption, increased investments in energy conservation measures and practices, larger monetary savings, and healthier indoor environments. Given the state of energy and electricity production in Lebanon, a NZEB approach offers households resiliency, independence, and autonomy. Moreover, NZEB will significantly lessen the financial burdens of Lebanese households. NZEB offer a robust path towards achieving environmental justice, social equity, and economic stability. A typical Lebanese household may experience a 90% reduction in energy consumption and associated expenditures. To that end, local household testimonials confirm that deployment of PV systems yielded 60-90% reduction in energy consumption and associated utility costs (60% reductions during the summer and 90% during the winter). Furthermore, when asked how satisfied with the installation of the PV system, households expressed a high level of content mainly due to experiencing independence from the extremely expensive and unreliable private generation market. These households indicated that they were forced to install PV systems since they couldn't financially afford relying on private-generation supply any longer. Private diesel generators now account for a 22-hour supply of electricity. As a result, private generation subscription fees have risen exponentially to as high as $375 a month, leaving many households struggling to make ends meet. The PV system deployment was the only economically viable and sustainable path left to take to preserve their livelihoods and achieve security and peace of mind. Lebanon has seen a spike in PV system installations over the past year primarily due to the unrelenting hyperinflation, persistent economic crisis, and severe power outages (1-2 hours of public power supply per 24hrs). Local solar companies are experiencing a massive boom in business, receiving more than 500 quote requests per week from homeowners and businesses. A standard PV system with ion battery storage capability could costs households anywhere between $4,500 and $6,000 or more, depending on KW capacity and input. Nevertheless, homeowners are opting to spend most of their hard-earned savings installing such systems to guarantee reliable access to power, ranging between 8 and 10 hours after the sun sets, with the promise of a 10-year or more system lifespan before any overhaul is needed. It's a classic deployment by necessity situation. If harnessed effectively, this bottom-up approach could lead to a renewable energy transformation in Lebanon, whereby decentralized reliable clean green power generation becomes wide-spread, transitioning the country closer to net zero energy generation and by default, less dependent on imported market-volatile fossil fuels. This might be a perfect opportune moment of inflection, whereby the country can undergo a tectonic paradigm shift from the bottom up. A NZEB approach might prove to be one of the most effective ways households can sustain their livelihoods and economic welfare, given the current conditions. Furthermore, NZEB would offer homeowner and tenants multiple benefits beyond the significant energy consumption reductions (Figure 181). Similarly, developers and builders would also benefit greatly from a NZEB approach, which is imperative to transform the existing residential construction market (Figure 182).

Homeowner Benefits

- Improved Indoor Environments
- Increased Property Values
- Reduced Operating Costs
- Reduced Energy Consumption
- Enhanced Resiliency and Independence
- Increased Monetary Savings

Figure 181. Household benefits and impacts of a NZEB approach

Developer Benefits

- Increased Savings associated with Design & Construction Costs
- Increased Asset Values
- Reduced Operating & Maintenance Costs
- Improved Tenant Experience
- Increased Financial Incentives
- Enhanced Exploitation Factor Allowances

Figure 182. Household benefits and impacts of a NZEB approach

If applied comprehensively, NZEB may have far reaching and overarching benefits including reductions in energy poverty and social inequity, economic independence and resiliency, and reductions in emissions associated air pollution (Figure 183). Furthermore, it also paves the path to the country's pledge of transitioning to renewable energy generation for the building sector by 2030 (18% of power demand and 11% of heat demand). similarly, a NZEB approach supports Lebanon's pledge to increase its GHG emission reduction targets from 15 to 20% by 2030. Lastly, a NZEB approach aligns perfectly with Lebanon's COP26 pledge to transition to NET Zero by 2050.

Paradigm Shift with NZEB - Benefits & Impacts
Resilience from Political Crises
Economic Independence
Social Equity
Safety & Resiliency
Elimination of Energy Poverty
Reduction of Environmental Degradation

Figure 183. National benefits and impacts of a NZEB approach

Implementation and Adoption

Adoption and proliferation of energy conservation and efficiency measures within the Lebanese residential sector have been slow at best, if not completely absent, outside of few voluntary initiatives. The four primary barriers include lack of public awareness, lack of enforcement mechanisms, lack of mandatory legislative policies for green construction and energy conservation, and a persistently unstable political and socio-economic situation. Overcoming these barriers requires a 3-prong multi-faceted approach encompassing financial, informational, and behavioral measures. First, financial incentives should be made available for energy efficiency upgrades, such as tax breaks, grants, long-term no-interest loans, etc. Second, access to reliable data, information, and tools should be made available to all stakeholders to best guide decision makers on the most optimal and viable solution to achieve zero-energy status. Third, addressing behavioral and cultural norms is imperative to trigger a paradigm shift in people's day-to-day actions and habits towards energy conservation. This study aims to address these barriers and opportunities by providing alternative solutions to existing building practices. Survey results showed a substantial interest in sustainability driven NZEB practices, where 86% of respondents expressed a high level of interest in Net Zero Energy Homes (93% of homeowners, 84% of students, 82 % of building professionals). At the same, survey findings revealed only 48% of total respondents were familiar with Zero Energy Homes (43% of homeowners, 34% of students, 66 % of building professionals). It's therefore imperative a holistic approach is adopted to address this significant knowledge gap to propagate NZEB practices successfully and effectively. To that end, several primary stakeholders should be targeted to help with implementation and adoption of Net Zero Energy Building practices in Lebanon's residential market. First, homeowners should be educated and made aware of NZEB practices and its overall benefits, financially and environmentally. However, it's paramount that financial incentives are made readily available for homeowners to take on such an approach and transition into zero-energy homes. Second, sustainability education should be comprehensively adopted in school curriculums from k12 to higher education. Moreover, NZEB practices should be introduced early on to students, especially within AEC disciplines. Third, building professionals need to be equipped with all the necessary tools and data to guide their decisions and fully embrace zero-energy methods and building practices. To that end, the Order of Engineers and Architects` *Thermal Standard* should be made mandatory. Furthermore, Lebanese construction law should include mandatory enforceable thermal standards such as insulation requirements and energy performance benchmarks and thresholds. Fourth, Developers and landlords should be offered incentives to build zero-energy apartment buildings. For example, the existing Lebanese construction law offers incentives to developers and builders (monetary, physical, FAR, allowable buildable area, etc.) to build exterior cavity double walls, whereby the area of the cavity walls can be deducted from the area of the apartment. Hence, developers and builders can exclude that area from the exploitation factors. Similar initiatives should be expanded to include insulation, HVAC, Glazing, PV, etc. Lastly, policy makers and legislators should introduce sustainability-driven initiatives/laws and make them mandatory, via an enforceable mechanism, to further promote NZEB practices nation-wide. Nonetheless, the bottom-up approach remains the most viable and effective method to generate a significant paradigm shift within the Lebanese residential market towards transitioning it into a more resilient and sustainable sector.

The most critical component to transitioning to NZEB is behavioral change and public awareness. Residential energy consumption is heavily dependent on behavior of household residents and their associated energy consumption patterns. It's therefore imperative that all stakeholders, including developers, builders, architects, apartment owners, tenants, understand energy consumption patterns and modes. It's also essential for them to be aware of the different ways they can conserve energy and the impact thereafter on their energy efficiency choices. Most importantly, stakeholders, especially homeowners, should be made aware of the multitude of benefits of energy conservation and efficiency, and the far-reaching impacts of their choices, decisions, and behavior. To that end, comprehending energy consumption patterns is the first element of the energy pyramid (Figure 184). It's the foundation from which NZEB practices should be initiated.

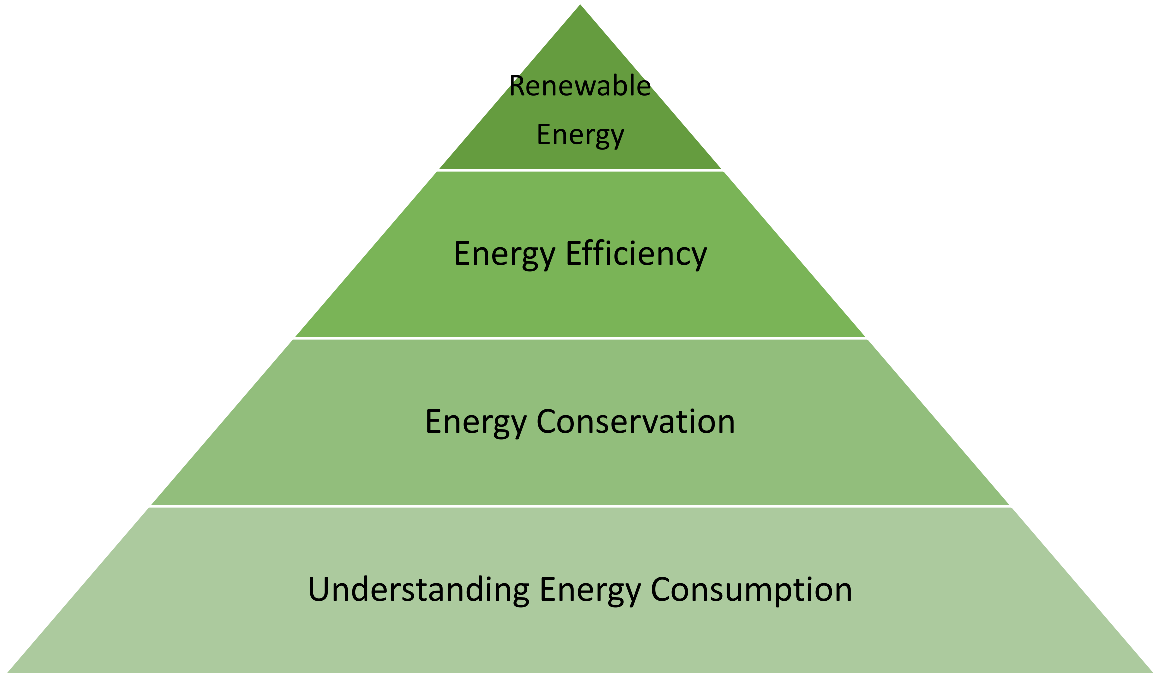

Figure 184. NZEB traditional energy pyramid structure and framework

Understanding energy consumption patterns is essential for energy conservation and efficiency practices. It requires homeowners and facility managers have access to reliable and up to date information. Nonetheless, the most critical message to all stakeholders is that energy-efficiency measures don't have to be costly and complex. Often, energy conservation measures are affordable, simple, and even free when passive strategies are employed. Once consumption patterns are understood, energy conservation is very heavily dependent on consumer behavior. Residents need to modify their current practices to save energy and consume it in a more efficient manner. That includes for example setting thermostats to higher setpoints during the summer and lower settings during the winter, turning lights off when rooms are not in use, switching TVs off when not watching, consolidating cooking schedules, and relying on passive free energy when available. Energy conservation behavioral modifications are often easily made at a small or no expense if people are made aware of their energy consumption patterns and impacts. To that end, access to information is essential to effectively educate consumers about energy conservation measures and to promote NZEB practices (Figure 185).

Figure 185. Access to information framework for energy conservation and NZEB practices

Access to information and data is essential in promoting Zero Energy Building practices as well as changing existing energy consumption patterns. At the same time, financial mechanisms are instrumental in providing equitable access to energy efficiency technologies and methodologies (Figure 186). Access to funds, in various forms, is essential for homeowner's ability to invest in transitioning their homes to NZEB structures. Moreover, access to funds is needed by all NZEB stakeholders including builders, developers, architects, and especially apartment owners and tenants. In the case of Lebanon, it's the only viable path forward given the current dire economic and financial situation in the country.

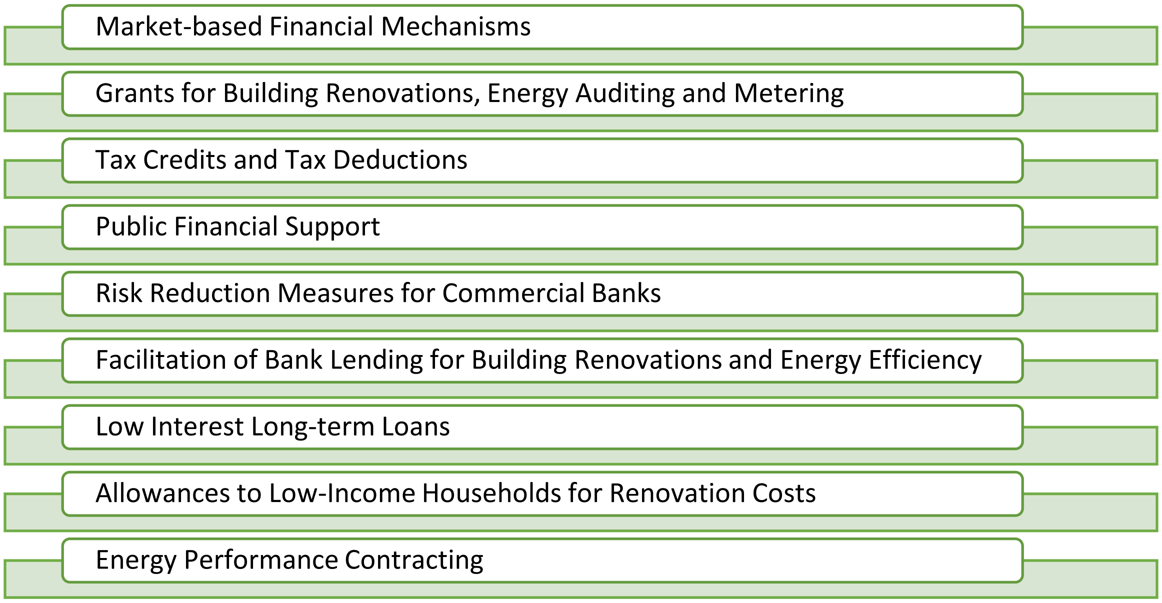

Figure 186. Financial mechanism tools for energy efficiency and NZEB practices

Behavioral change coupled with information access and financial incentives are essential mechanisms by which NZEB practices could be implemented, and energy conservation and efficiency measure made more widely adopted within the Lebanese residential market. These three gaps need to be identified and addressed to generate a paradigm shift in existing design methodologies, construction practices, and energy consumption patterns.

Lebanon is currently experiencing 4 catastrophic events, a tenacious political crisis, a systemic economic crisis, and a deepening financial crisis. Moreover, the current pandemic has further aggravated the already unstable existing socio-economic situation. The country's economy has completely collapsed under the weight of the dueling political and health crises. Social unrest has become prevalent and widespread across all sectors of the population, but especially among the middle- and low-income populations. In 2021, the World Bank, rated Lebanon's crisis among the world's worst since the 1850s. The confluence of the political, social, health, financial and economic crises has resulted in massive inflation unseen since the civil war. To that end, Lebanon surpassed Zimbabwe and Venezuela for the most hyperinflation in the world in 2021. Lebanese currency has been severely devalued due to hyperinflation to the point that it has lost more than 90% of its value since October 2019. For example, the one US dollar exchange rate of 1500 Lebanese pounds from a year ago is now up to approximately 30,000 Lebanese pounds (*when the report was written, 2021-2022)*. As a result, the country's social safety nets have been obliterated. These mounting and intensifying crises has affected all sectors of society. However, the middle to low-income population has been hit the hardest. Lebanon is on the brink of total collapse. A United Nation's ESCWA 2021 policy brief reported 4 million residents of Lebanon (82% of population) suffer from multidimensional poverty. Furthermore, a *Human Rights Watch* 2022 World Report shows 80% of Lebanon's population without access to basic rights like, health, education, electricity, and housing (Human Rights Watch, 2022). This research is a small but necessary step towards highlighting feasible ways Lebanese can improve their access to basic right such as electricity and energy. The study aims to provide stakeholders including homeowners, building professionals, and others the necessary means and methods to initiate such a transformational change. The research's objective is to promote sustainable residential building practices that offer households a path towards achieving social equity, economic stability, and most importantly reducing energy poverty and inequities. Research findings clearly show that NZEB are feasible and viable as an innovative design and construction paradigm, transitioning Lebanon's multi-family residential market into a NZE sector.

While the research findings provided a clear and systematic road map to achieving Net Zero Energy in apartments buildings in Lebanon, encompassing a compact and massing form coupled with several high efficiency and conservation measures, it's worth noting that architects and designers should pay close attention to design aesthetics and overall building appeal. It's critically imperative to balance performance and design aesthetics while striving to achieve optimum comfort for occupants. The high performance NZEB design generated by this research could be very easily enhanced aesthetically via few strategic design measures without compromising performance. Breaking the block-like massing in strategic locations coupled with material applications could transform the standard archetype of a residential building block into a more inviting and inspiring building form.

Future Work

Even though this research project is contributing new knowledge on NZEB practices and approaches in Lebanon, there remain several areas in need of further development and exploration. A future phase of this research will entail a comprehensive on-site surveying of existing Lebanese apartment buildings to better understand local existing conditions as well as contextual factors. To that end, the research had already started this process by surveying households in the town of Bishmizzine, albeit on a limited basis due to COVID constraints and restrictions. Future phases of this survey will encompass extensive data collection and gathering of actual energy use and electricity consumption from homeowners and various tenants in the region of the study and beyond. Thereafter, data will be compared to the baseline energy modeling results to better normalize the results. The objective of the on-site surveys is to establish an average real-time baseline for energy consumption. Another future phase of the research will expand to include detached single-family homes that remain heavily unregulated. A comprehensive life-cycle cost analysis and cost to benefit impact study would also be recommended for future examination and exploration. Another future phase of the research would aim to develop a fully functional interactive mobile app to educate and inform the public about best practices and strategies for the design and adoption of NZEB in Lebanon and the region. The App would offer an interactive educational and informational platform. Moreover, it would enable homeowners and other stakeholders the ability to find resources readily and easily. Studies have shown that Apps with direct feedback systems are successful in motivating households to adjust their energy consumption levels. Lastly, a policy approach to NZEB should be explored to systematically integrate it into existing thermal standards and construction laws. The study's proposed NZEB bottom-up approach is currently the most effective methodology in a nation like Lebanon, plagued by archaic and corrupt bureaucracies. However, it's imperative to develop and adopt enforceable legislative mechanisms and frameworks via robust mandatory policies and initiatives, to sustain and support such an approach well into the future.

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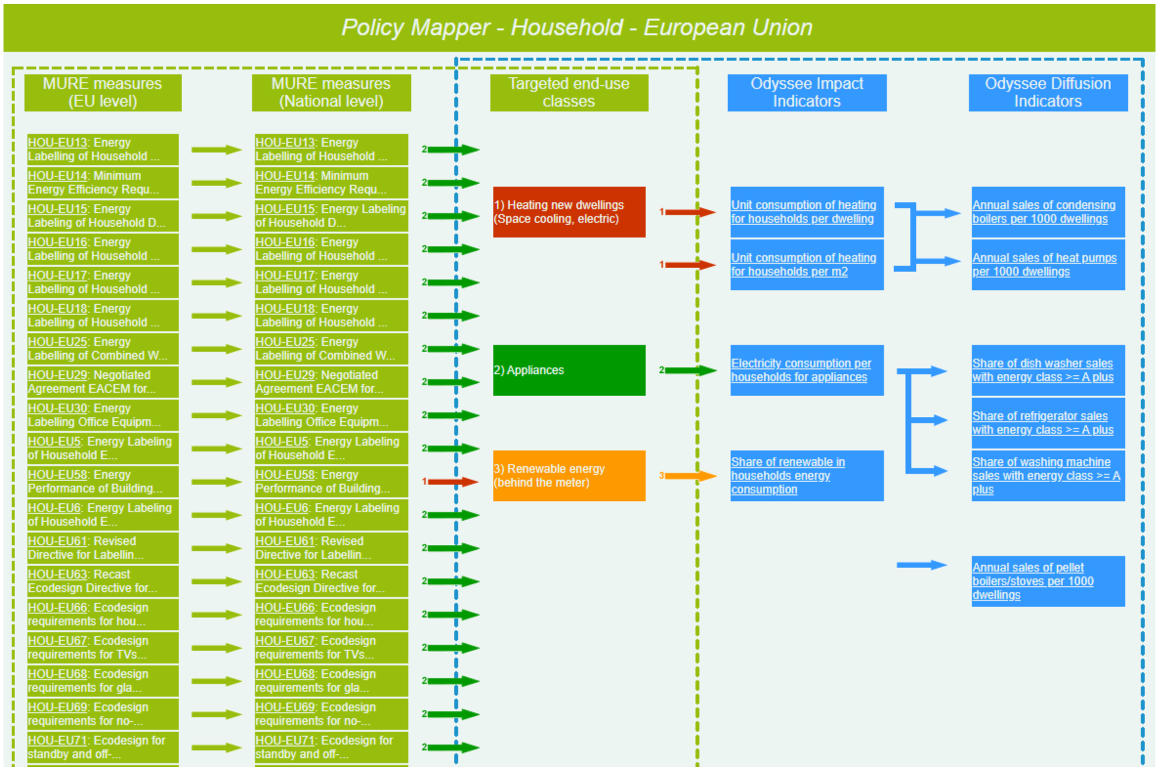
Appendix A: EU Residential Household Residential Policy Mapper



Policies by Topics

Select the Topic from the list beside | Measures on energy efficiency and renewable energy in buildings ▾ | Include completed measures ☑

	For energy audits (Household)	For investment in renewables (Household)	For investments in energy efficient building renovation (Household)	For investments in new buildings exceeding building regulation (Household)	Income tax credit (Household)	Income tax reduction (Household)	Mandatory audits in large residential buildings (Household)	Mandatory audits in small residential buildings (Household)	Mandatory energy efficiency certificates for existing buildings (Household)	Mandatory energy efficiency certificates for new buildings (Household)	Energy Performance Standards (Household)	Minimum thermal insulation standards (Household)	Technology procurement for energy efficient buildings / components (Tertiary)	Financial incentives for architects who integrate EE measures (Tertiary)	For energy audits/training/benchmarking activities (Tertiary)	For energy efficiency investment (Tertiary)	For investment in renewables (Tertiary)	Mandatory audits in large tertiary sector buildings (Tertiary)	Mandatory audits in small tertiary sector buildings (Tertiary)	Mandatory energy efficiency certificates for buildings (Tertiary)	Energy Performance Standards (Tertiary)
Austria	0	2	1	1	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0
Belgium	1	1	1	2	0	2	0	0	2	2	2	2	0	1	1	4	2	1	0	3	4
Bulgaria	0	1	7	0	0	0	1	0	1	0	3	2	0	0	0	3	1	2	1	3	2
Croatia	0	2	6	1	0	0	0	0	1	1	5	1	0	0	2	5	4	1	1	1	0
Cyprus	2	2	1	0	0	0	0	0	1	1	3	0	1	0	2	3	2	0	0	1	1
Czech Republic	1	2	5	0	0	0	0	0	2	2	4	1	2	0	0	7	5	0	0	0	1
Denmark	0	1	0	0	0	0	0	0	0	0	3	2	0	0	0	0	0	0	1	0	1
Estonia	2	1	6	1	1	1	1	1	1	1	2	2	0	2	1	11	1	0	0	1	3
European Union	0	0	0	0	0	0	0	0	2	2	2	3	1	0	0	0	0	0	0	0	4
Finland	1	1	1	0	0	1	0	0	1	1	4	1	0	0	2	4	2	0	0	1	1
France	2	2	5	2	2	4	2	0	1	1	7	1	0	0	2	4	1	5	1	0	5
Germany	3	1	3	1	0	0	1	1	2	1	4	3	0	0	2	8	1	1	1	1	5
Greece	2	1	3	0	0	0	2	2	1	1	4	1	2	0	2	4	1	4	3	0	3
Hungary	0	2	3	1	0	0	0	0	1	1	1	1	0	0	2	8	5	0	0	0	0
Ireland	0	1	4	2	0	0	0	0	2	2	7	0	1	0	1	6	1	1	0	0	7
Italy	0	1	1	0	0	1	0	0	1	1	5	4	0	0	0	2	3	1	0	4	5
Latvia	1	2	3	1	0	1	0	0	2	2	3	3	1	0	0	11	11	3	0	2	1
Lithuania	0	1	6	0	0	0	0	0	0	0	2	5	0	0	0	17	2	0	0	0	0
Luxembourg	2	2	2	2	0	0	0	0	2	2	2	3	0	0	0	0	0	0	0	2	4
Malta	3	6	4	0	0	0	0	1	0	0	1	1	1	0	0	3	1	1	1	1	0
Netherlands	2	4	11	1	0	0	0	0	1	0	5	0	1	0	0	4	2	0	0	0	1
Norway	1	1	3	2	0	0	0	0	1	1	5	4	0	0	2	5	3	0	0	1	1
Poland	0	2	0	1	0	0	0	0	1	1	2	0	0	0	0	7	3	0	0	0	0
Portugal	0	1	0	0	0	0	0	0	1	4	3	2	0	0	0	1	1	2	1	4	3
Romania	0	2	2	0	0	0	0	0	1	1	2	0	0	0	0	1	1	2	0	2	4
Serbia	0	0	1	0	0	0	0	0	1	1	1	0	1	1	1	2	0	0	0	0	2

Policy Matrix	Supporting Measures							Targets					
Countries	Labeling Schemes	Certification Schemes	Education	Access	Incentives	Training	Links	Conservation	Efficiency	Performance-based	ZNEB	Smart Metering	Emissions
Cyprus	Yes	Yes	Yes	Yes	Yes	Yes	https://epbd	Yes	Yes	Yes	Yes	Yes	Yes
Denmark	Yes	Yes	Yes	Yes	Yes	Yes	Denmark: htt	Yes	Yes	Yes	Yes	Yes	Yes
Finland	Yes	Yes	Yes	Yes	Yes	Yes	Finland: http	Yes	Yes	Yes	No	Yes	Yes
France	Yes	Yes	Yes	Yes	Yes	Yes	France: https	Yes	Yes	Yes	Yes	Yes	Yes
Germany	Yes	Yes	Yes	Yes	Yes	Yes	Germany: htt	Yes	Yes	Yes	Yes	Yes	Yes
Greece	Yes	Yes	Yes	Yes	Yes	Yes	Greece: https	Yes	Yes	Yes	Yes	Yes	Yes
Israel	No	No	Yes	Yes	Yes	Yes	https://www.	Yes	Yes	No	No	No	Yes
Italy	Yes	Yes	Yes	Yes	Yes	Yes	Italy: https://	Yes	Yes	Yes	Yes	Yes	Yes
Lebanon	No	No	No	No	No	No	https://globa	Yes	Yes	No	No	No	No
Portugal	Yes	Yes	Yes	Yes	Yes	Yes	Portugal: http	Yes	Yes	Yes	No	Yes	Yes
Spain	Yes	Yes	Yes	Yes	Yes	Yes	Spain: https:	Yes	Yes	Yes	No	Yes	Yes
The Netherlands	Yes	Yes	Yes	Yes	Yes	Yes	The Netherla	Yes	Yes	Yes	Yes	Yes	Yes
UK	Yes	Yes	Yes	Yes	Yes	Yes	UK: https://w	Yes	Yes	Yes	Yes	Yes	Yes

EBPD: https://epbd-ca.eu/wp-content/uploads/2019/09/CA-EPBD-2018-BOOK-VOLUME-I.pdf
Mure: https://www.odyssee-mure.eu/publications/efficiency-trends-policies-profiles/
IEA: https://www.iea.org/countries/
GBPN: http://www.gbpn.org/databases-tools/purpose-policy-tool-new-buildings
OECD: https://www.compareyourcountry.org/environmental-policy-stringency-indicators

Instruments and Measures by Measure Type in the Residential Sector Implemented in the EU Member States

LEGENDA) Status: =OnGoing =Completed =Proposed =Unknown - ***Impact Evaluation:*** **L**= Low, **M**= Medium, **H**= High, **U**= Unknown

		EU
	Legislative/Normative	
	Mandatory Standards for Buildings	
1	Energy Performance Standards	
2	Minimum thermal insulation standards	
	Regulation for Heating Systems and hot water systems	
3	Minimum efficiency standards for boilers	
4	Compulsory replacement of old boilers above a certain age	
5	Thermostatic zone control	
6	Control systems for heating (Regulation)	
7	Mandatory heating pipe insulation	
8	Periodic mandatory inspection of boilers	
9	Periodic mandatory inspection of Heating/Ventilation/AC (HVAC)	
10	Mandatory use of solar thermal energy in buildings	
	Other Regulation in the Field of Buildings	
11	Individual billing (multi-family houses)	
12	Maximum indoor temperature limit(s)/limitation heating period	
	Mandatory Standards for Electrical Appliances	
13	Minimum efficiency standards for electrical appliances	
14	Mandatory measures for efficient lighting	
	Legislative/Informative	

Appendix B: Zero Energy Buildings Database Mapper

Green Strategies			Passive							Active			
Location	Projects	Location-Year	Daylight	Operable Windows	Thermal Mass	Natural Ventilation	Water Conservation	Shading Systems	Super Insulation	HP HVAC	HP Windows	RE Systems	Labels
Cyprus	PH Tseri	Tseri - 2016	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Passive
Denmark	Net zero-energy Home	Århus - 2010	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	ZEB
Finaland	VILLA ISOVER	Hyvinkää - 2013	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	ZEB
France	First passive house Premium	La Crau - 2017	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	ZEB-Passive
Germany	House on the Mountain	Sulzberg - 2014	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	ZEB-Passive
Greece	Passivistas:TheHouseProject	Papagos - 2015	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Passive
Israel	Cannabis eco-house	Ein Hod - 2016	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No
Israel	Residence in the Galilee	Tiberias - 2016	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No
Israel	Ecological House	Tel Aviv - 2018	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No
Israel	Eco360 Energy Positive Villa	Arsuf - 2018	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No
Italy	Project Botticelli	Sicily - 2012	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	ZEB-Passive
Lebanon	Beit Misk Community	Metn - 2009	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	BREEAM
Lebanon	Zgharta House	Zgharta - 2015	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	No
Portugal	Rua do Mar		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Passive
Spain	Reused Sea Container House	Mutxamel - 2015	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	EPC
The Netherlands	Net zero-energy 'flat	Utrecht - 2016	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	EPC
UK	Steel Farm	Hexham - 2013	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Passive

Appendix C: Call and information sheet for survey Respondents

Perception of Zero Energy Homes (ZEHs) Survey

A doctoral research project by Naim Jabbour at the School of Architecture at Carnegie Mellon University

Call and Information Sheet for Survey Respondents

Please **read** carefully and **share** with other potential respondents who might be interested

About the survey and its purpose

This 10-15-minute survey is intended for data collection regarding Zero Energy Homes (ZEHs). It includes questions about knowledge of ZEHs, interest in ZEHs, perceptions of ZEHs, and barriers to ZEHs. It also includes few questions about the performance of participant's own home or place of residence.

Who is the survey for?

You should participate in the survey if you're a current homeowner, renter, prospective homeowner, anyone planning for a future residence, student, or a building professional.

Link to access the survey

Your participation will require approximately 10-15 minutes. To access the survey, click the following link: https://forms.gle/hQ1KGmEmoqPRx2HT9

The outcome and contribution of the survey

This survey is part of a larger study titled *Design Optimization for Net Zero Energy Apartment Buildings in Lebanon: A parametric performance analysis of a Residential Case Study.*

The purpose of the study is to help all populations living in regions with Mediterranean climate (like Lebanon) cope with residential energy use and its impacts. The study aims to analyze the impact of building upgrades on energy performance in a standard Lebanese apartment building to provide comprehensive guidelines to affect new sustainable residential building paradigms & practices. The research aims to minimize the impact of the residential sector on energy use and air pollution in regions with Mediterranean climates such as Lebanon.

The study will examine the impacts of various building upgrades on energy consumption in a standard Lebanese apartment building. The findings of the study will be used to provide optimal architectural guidelines for the design of high-performance Net Zero Energy apartment buildings. Furthermore, the study will provide comprehensive guidelines to promote sustainable residential building practices. Lastly, the findings of the study will be utilized to provide a comprehensive design framework for achieving Net Zero Energy residential buildings in Lebanon.

Ethics clearance
The survey is approved by the Institutional Review Board (IRB) of Carnegie Mellon University. All data will be strictly confidential and will be de-identified. You are not obliged to respond to all questions. In addition, your participation in the survey is voluntary.

What happens next?
The reported results will be analyzed and be integrated in the research. It also may be used in publications and presentations.

About the researcher: Naim Jabbour
Naim Jabbour is currently pursuing a Doctor of Design in Architecture at Carnegie Mellon University, writing a thesis about Net Zero Energy residential buildings in Lebanon. He's an Assistant Professor of architecture and sustainable design at Penn College, an affiliate of Penn State University. Naim earned his Bachelor of Architecture degree from Louisiana State University, followed by two master's degrees: a Master of Science in Architecture from Carnegie Mellon University and Master of Liberal Arts in Sustainability from Harvard University. He also earned several post-graduate sustainability certificates from Harvard University. On the professional side, his tenure encompassed an eight-year position as a project designer/executive at PBK, a top tier national design firm located in Houston Texas. He also served as a National Chair at the Center for Green Schools within the US Green Building Council. Naim practices architecture on a part-time basis in his home country of Lebanon. He's also a LEED accredited professional and an Associate AIA. Naim is heavily invested in sustainability and environmental stewardship.

Naim's interest in building performance and Zero Energy buildings began while practicing architecture, where he got the chance to work on several sustainable projects (LEED Buildings). Later on, he was able to expand on his interests in sustainability by pursuing graduate studies at Carnegie Mellon university in 2008. Those interests materialized into a thesis project while pursuing graduate studies at Harvard University in 2018. His thesis explored and analyzed the impact of varying architectural variables on building performance in a Pennsylvania single family home.

Naim’s long-term goal is to promote and advance sustainable residential practices in Lebanon. He hopes the findings of his research will be used by policy makers, buildings professional, and homeowners to adopt robust green building practices and policies in Lebanon, leading to a more resilient and sustainable built environment. For further questions, please contact Naim Jabbour at: njabbour@andrew.cmu.edu

Appendix D: Survey Questions (USA, Lebanon)

Add Links

Appendix E: Thermal Standard for Buildings in Lebanon 2010

Table 4: Reference Thermal Resistance and Width of Thermal Insulation for Slab on Ground R-ref (m^2.K/W) vs. climatic zone (source PEEC and TSBL 2005)

Climatic Zone	Building Category	Minimum Thermal Resistance, R (m^2.K/W)	Insulation width (m)
1	1 and 2	NR	NR
2	1 and 2	0.75	1.00
3	1 and 2	1.00	1.25
4	1 and 2	1.25	1.50

Table 5: Reference U-value of façade of buildings vs. climatic zone U_{Fref}

Climatic Zone	Building Category	U_{Fref} (W/m^2.K)
1 Coastal Zone	1 Res.	2.5
	2 N Res.	2.2
2 Western mid mountain	1 Res.	1.5
	2 N Res.	1.3
3 Inland Plateau	1 Res.	1.5
	2 N Res.	1.3
4 High Mountain	1 Res.	1.2
	2 N Res.	1.0

Table 6 - Architectural Shading Factor (ASF) for Windows Protected by Overhangs Only

PF – Overhangs	ASF per orientation			
	N NE,NW	E EN,ES	W WN,WS	S SE,SW
PF ≤ 0.05	0.70	1	1	1
0.05 < PF ≤ 0.15	0.70	1	1	0.9
0.15 < PF ≤ 0.25	0.70	1	1	0.80
0.25 < PF ≤ 0.40	0.70	1	1	0.75
PF >0.40	0.70	1	1	0.70

Table 7 - Architectural Shading Factor (ASF) for Windows Protected by Fins Only

PF – Fins	ASF per orientation			
	N NE,NW	E EN,ES	W WN,WS	S SE,SW
PF ≤ 0.05	0.70	1	1	1
0.05 < PF ≤ 0.15	0.70	0.95	0.95	1
0.15 < PF ≤ 0.25	0.70	0.90	0.90	1
0.25 < PF ≤ 0.40	0.70	0.85	0.85	1
PF >0.40	0.70	0.80	0.80	1

Table 8 - Architectural Shading Factor (ASF) for Windows Protected by Fins and Overhangs

PF – Fins and overhangs	ASF per orientation			
	N NE,NW	E EN,ES	W WN,WS	S SE,SW
Overhangs: PF ≤ 0.05 Fins: PF ≤ 0.05	0.70	1	1	1
Overhangs : 0.05 < PF ≤ 0.15 Fins : 0.25 < PF ≤ 0.40	0.70	0.95	0.95	0.90
Overhangs: 0.15 < PF ≤ 0.25 Fins: 0.25 < PF ≤ 0.40	0.70	0.90	0.90	0.80
Overhangs: 0.25 < PF ≤ 0.40 Fins : 0.25 < PF ≤ 0.40	0.70	0.85	0.85	0.75
Overhangs: PF > 0.40 Fins: Overhangs: PF > 0.40	0.70	0.80	0.80	0.70

Table 9: Reference Window to Wall Ratio (WWR-ref)

Climatic Zone	Building Category	Maximum Reference Window to Wall Ratio WWR-ref
1 Coastal Zone	1 Res.	0.22
	2 N Res.	0.21
2 Western mid mountain	1 Res.	0.21
	2 N Res.	0.20
3 Inland Plateau	1 Res.	0.20
	2 N Res.	0.19
4 High Mountain	1 Res.	0.21
	2 N Res.	0.20

Table 10: Reference specific thermal energy needs (for cooling and Heating) by category of building vs. climatic zone

Climatic Zone	Building Category	Maximum Reference specific thermal energy cooling and heating needs Eref (kWh/m^2.year)
1 Coastal Zone	1 Res.	**80**
	2 N Res.	**85**
2 Western mid mountain	1 Res.	**90**
	2 N Res.	**95**
3 Inland Plateau	1 Res.	**85**
	2 N Res.	**90**
4 High Mountain	1 Res.	**100**
	2 N Res.	**110**

Table 11A: Building Envelope Requirements for Residential Buildings in Climate Zone 1 (Coastal)

Window to Wall Ratio WWR (%)	U-value Roof $W/m^2.K$	U-value Wall $W/m^2.K$	U-value Wind. $W/m^2.K$	SHGC*
≤ 15 %	0.71	1.60	5.8	North: NR All: NR
16 – 25 %	0.71	1.60	5.8	North: NR All:0.7
26 – 35 %	0.71	1.60	4.0	North: NR All:0.6
36 – 45 %	0.71	1.26	3.3	North:0.7 All:0.4
Skylight			U-value Skylight $W/m^2.K$	SHGC
≤ 2 %			5.8	0.4
2.1-5.0 %			5.8	0.2

Table 13A: Building Envelope Requirements for Residential Buildings in Climate Zone 3 (Inland Plateau)

Window to Wall Ratio WWR (%)	U-value Roof $W/m^2.K$	U-value Wall $W/m^2.K$	U-value Wind. $W/m^2.K$	SHGC*
≤ 15 %	0.63	0.77	4.0	North: NR All: NR
16 – 25 %	0.63	0.77	4.0	North: NR All:0.7
26 – 35 %	0.63	0.57	3.3	North:0.6 All:0.5
36 – 45 %	0.55	0.57	2.6	North:0.5 All:0.4
Skylight			U-value Skylight $W/m^2.K$	SHGC
≤ 2 %			4.0	0.4
2.1- 5.0 %			3.3	0.2

Building Board

Description	Density kg/m^3	Conductivity W/(m·K)
Gypsum or plasterboard, 0.5 in	800	0.160
Plywood (Douglas fir)	545	0.115

Insulation

Description	Density kg/m^3	Conductivity W/(m·K)
Cellular glass	136	0.050
Glass fiber, organic bonded	64 to 144	0.036
Expanded perlite, organic bonded	16	0.052
Expanded rubber (rigid)	72	0.032
Expanded polystyrene extruded, Cut cell surface	29	0.036
Expanded polystyrene extruded, Smooth skin surface	29 to 56	0.029
Expanded polystyrene, molded beads	16	0.029
	20	0.036
	24	0.035
	28	0.035
	32	0.033
Cellular polyurethane (R11 exp.)(unfaced)	24	0.023
Polyisocynaurate (R11 exp.)	32	0.020
Mineral fiber with resin binder	240	0.042
Mineral fiberboard, wet-felted, Core or roof insulation	256 to 272	0.049
Mineral fiberboard, wet-felted, Acoustical tile	288	0.050

Loose Fill

Description	Density kg/m^3	Conductivity W/(m·K)
Perlite, expanded	80 to 128	0.053
Vermiculite, exfoliated	112 to 131	0.068

Woods

Description	Density kg/m^3	Conductivity W/(m·K)
Maple, oak, and similar hardwoods	720	0.16
Fir, pine, etc.	510	0.12

Masonry materials / Concrete

Description	Density kg/m^3	Conductivity W/(m·K)
Cement mortar	1860	0.73
Sand and gravel or stone aggregate (not dried)	2240	1.75

Masonry units

Description	Density kg/m^3	Conductivity W/(m·K)
Brick, common	1920	0.72
Brick, face	2080	1.30

Wall Construction

Description	Thickness E (cm)	Thermal Resistance R m^2.K/W
Concrete block Lightweight	5	0.05
Concrete block Lightweight	8	0.06
Concrete block Lightweight	10	0.08
Concrete block Lightweight	14	0.09
Concrete block Lightweight	20	0.14

Roof Construction

Description	Thickness E (cm)	Thermal Resistance R $m^2.K/W$
Hollow block Concrete “Hourdis”	18	0.18
Hollow block Concrete “Hourdis”	20	0.20
Hollow block Concrete “Hourdis”	25	0.23
Hollow block Concrete “Hourdis”	30	0.25

U values of building assemblies

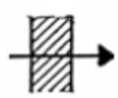
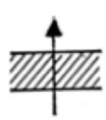
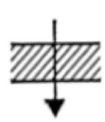
Coefficients of transmission *U* for wood doors ($W/m^2 \cdot K$)

Thickness	Description	Winter			Summer
		21°C inside temperature			24°C inside temperature
		No storm door	Wood storm door (50% glass)	Metal storm door	No storm door
35 mm	Hollow-core flush door	2.7	1.7	1.8	2.6
35 mm	Solid-core flush door	2.2	1.5	1.6	2.2
44 mm	Solid-core flush door	1.9	1.6	1.4	1.8

Overall coefficients of heat transmission U of windows assemblies and skylights ($W/m^2 \cdot K$) – Including Frame.

			Single Pane	Double Pane					
			No air space	5 mm air space	6 mm space	13 mm air space			
			No low-E coating SCg = 0.94	No low-E coating SCg = 0.84	No low-E coating SCg = 0.84	No low-E coating SCg = 0.84	Low-E coating SCg = 0.6	Low-E coating SCg = 0.4	Low-E coating SCg = 0.2
No storm sash	***No shade***	Winter	5.8	4	3.8	3.3	2.6	2.2	1.8
		Summer	5.7	3.9	3.7	3.2	2.4	2.7	2.2
Exterior horizontal panels (skylights)		Winter	7.0	4.0	3.7	3.4	2.7	3.0	3.2
		Summer	4.7	3.2	3.1	2.8	2.0	2.4	2.6

ANNEX 4: Thermal Resistance of air films

Wall and Roof positions and Heat)Flow direction		**Thermal resistance of air films ($m^2.K/W$)**					
		Wall or Roof in contact with: - **Outside** - **an open passage** - **an open room**			**Wall or Roof in contact with,** - **another room, heated or not** - **a roof space** - **a ventilation space**		
		1/hi	**1/he**	**1/hi+1/he**	**1/hi**	**1/he**	**1/hi+1/he**
Wall that is vertical or forms an angle greater than 60° with the horizontal		**0.11**	**0.06**	**0.17**	**0.11**	**0.11**	**0.22**
Roof that is horizontal or forms an angle less than 30° with the horizontal, Rising flow (roof)		**0.09**	**0.05**	**0.14**	**0.09**	**0.09**	**0.18**
Roof that is horizontal or forms an angle less than 30° with the horizontal. Descending flow (roof)		**0.17**	**0.05**	**0.22**	**0.17**	**0.17**	**0.34**