Adaptive Retrofit Guidelines for Traditional Lebanese Houses

A Balance Between Energy, Comfort, and Built Identity

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إرشادات التكييف والتحديث للمنازل اللبنانية التقليدية

التوازن بين الطاقة والراحة والهوية المعمارية

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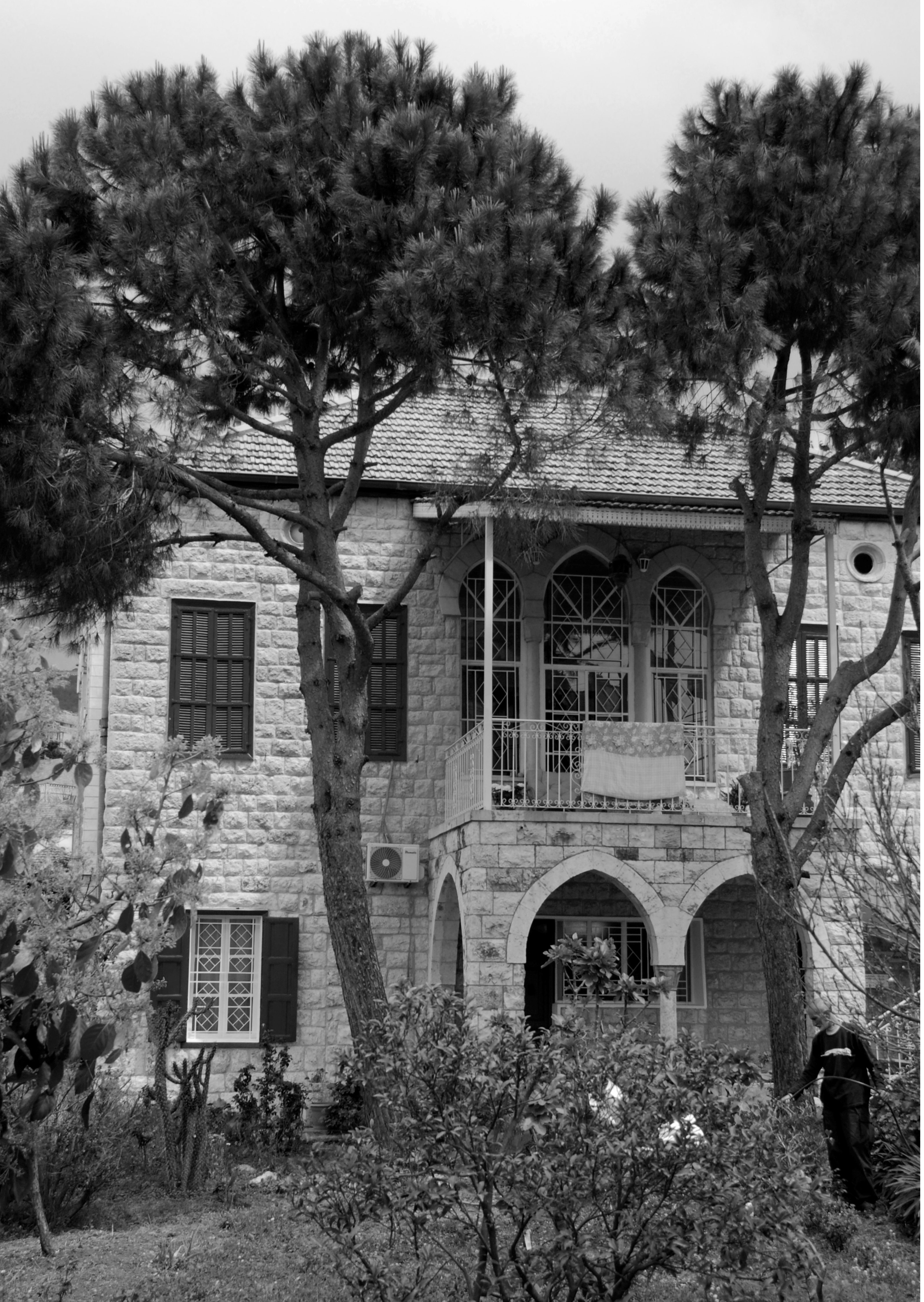

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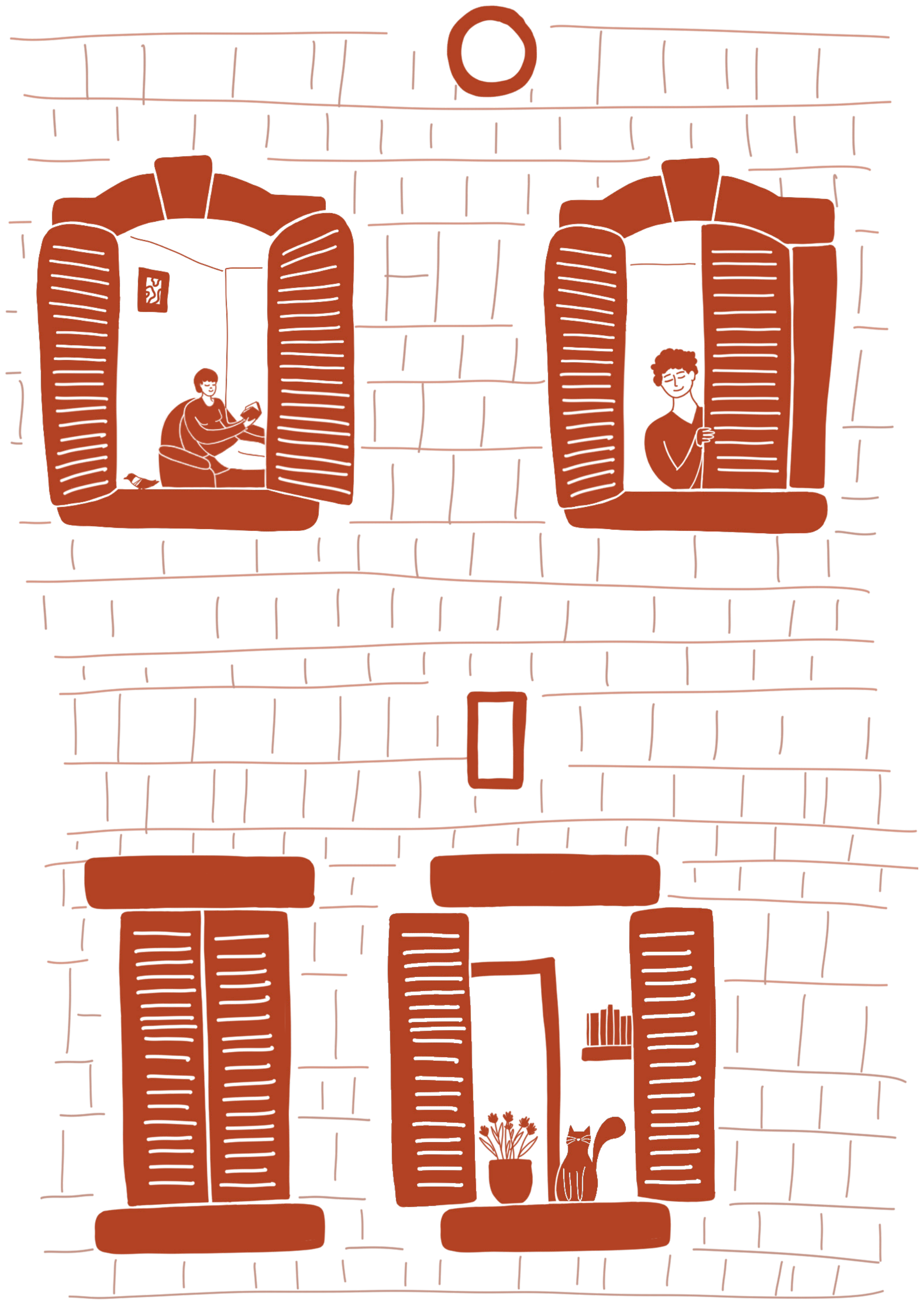
I dedicate this work to my parents, my sister, my family and Nick whose support from a distance got me through the finish line.

To my friends back in Lebanon and all over the world.

To my friends who have been like a second family since the day I moved to Turin.

To my beautiful country, who I hope will one day get the chance to flourish and thrive.



ABSTRACT

As our world faces rapid environmental, societal and technological shifts, architecture must evolve in parallel - not only in form and function, but in responsibility. Traditional Lebanese houses -built from locally sourced materials- are culturally significant and structurally resilient yet often fall short of modern thermal comfort standards. In light of rising climate goals and energy efficiency demands, our tangible heritage has more chances of being preserved instead of demolished, if it follows responsible adaptation that enables these structures to serve as durable and sustainable homes.

This thesis examines a typical two-story Central Hall House from the 19th century, located in Lebanon's mountainous Csa climate zone. Using a mixed-methods approach -combining interviews, spatial observations, climatic analysis and energy simulations- the study assesses the building's thermal performance under existing and retrofitted scenarios. The results establish a comprehensive guideline that ranges from low- to high-impact retrofit strategies correlated with progressive improvements in both thermal comfort and energy efficiency.

The findings demonstrate that vernacular typologies can be effectively adapted through flexible, climate-responsive design, offering a framework of retrofit strategies that align with varying levels of intervention and occupant preferences.

Keywords:

Cultural Identity
Energy Efficiency
Vernacular Architecture
Adaptive Retrofit
Climate Responsive Design

فهرس المحتويات

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01 INTRODUCTION

01

Lebanon 's geopolitical location has made it a zone of perpetual instability and recurrent conflicts, putting our architectural cultural heritage at constant risk. Despite the historical and social value of traditional Lebanese houses, state-led preservation efforts and protective legislation remain limited, and as a result, the initiative to restore and reuse the traditional houses often arises from individuals and private entities.

The construction of those traditional stone houses was dictated by a combination of geographical, geological, and cultural factors. Practical constraints such as the availability of materials, the structural considerations, and the cultural and architectural norms led to the development of typologies characterized by certain repetitive dimensions and spatial patterns, reflecting both environmental adaptation and socio-cultural identity. However, those houses are increasingly under threat from neglect, unstainable urbanization and modern comfort expectations.

As Victor Olgyay emphasized in Design with Climate (1963), architecture must respond to both its climatic and cultural context. This remains highly relevant today as we face rising environmental pressures and the urgent need to shift toward Net-Zero –or even carbon-negative- building strategies. The use of existing structures not only preserves cultural identity but also contributes to sustainable development by minimizing waste and reducing reliance on new materials that deplete resources and require high embodied energy. Despite their architectural resilience, traditional Lebanese houses often fail to meet today's thermal comfort standards, particularly in the face of extreme temperatures and humidity fluctuations. With the existing dependence on air conditioning and gas heating, the use of vernacular building techniques is declining, and the exploitation of the existing passive strategies is often being completely overlooked, labeled as no longer suitable for modern comfort needs.

Additionally, restoration efforts prioritize visual or structural preservation while neglecting the building's energy performance and interior comfort levels.

This reliance on the energy grid is especially problematic in Lebanon, where the national power grid is highly unreliable -a situation that has worsened in the recent years due to political and economic instability. As a result, many households frequently experience prolonged power outages, leaving homes without access to consistent electricity, making consistent indoor thermal comfort difficult to maintain. In this context, reducing dependence on the public energy grid and promoting energy self-sufficiency through resilient building strategies becomes not only a sustainable solution but an essential one. Ensuring comfort through passive and renewable energy-based solutions is critical to preserving these buildings in a way that is both culturally and environmentally respectful and resilient.

This thesis investigates how traditional Lebanese houses, specifically the Central Hall House typology, respond to their local climate and how they can be retrofitted to achieve both thermal comfort and energy efficiency. This typology was selected due to its widespread distribution across the Lebanese territory, and the representative house used in this research is a 19th century typical Central Hall House located in Mtain, a village nestled in Lebanon's mountainous region, within a typical Mediterranean climate. Although the physical building is no longer accessible, it was reconstructed based on documentation from Friedrich Ragette's Architecture in Lebanon -specifically the Anis Haddad House built in 1886 alongside general knowledge and research on Central Hall Houses. The reconstruction and adapted climate data served as the foundation for the thermal and energy simulations used in this research.

The goal is to offer a framework of sustainable refurbishment strategies that balance thermal comfort and energy performance, respecting the existing building's constraints and maintaining visual integrity without compromising their architectural identity. By evaluating a range of intervention levels through both qualitative and simulation-based analysis, the thesis aims to demonstrate how vernacular typologies can evolve responsibly, offering resilient and culturally rooted solutions for a changing climate.

Motive

The geopolitical location of Lebanon makes it a zone of perpetual instability and recurrent conflicts, putting at constant risk the disappearance of our cultural heritage, and it is often at the scale of an individual and the private sector that the initiative to restore and reuse Lebanese traditional houses comes from.

Traditional Lebanese houses, in all their architectural variations, can still be found across the country. While many are still inhabited, a significant number remain abandoned and in a state of deterioration.[1] This is largely due to a growing preference for modern apartment living, which is seen as more practical and comfortable.

One of the main reasons for this shift is that traditional houses often fall short of modern thermal comfort standards. Their larger volumes are difficult to heat and cool efficiently, leading to high energy costs and discomfort in extreme weather. This makes them less appealing to live in and, consequently, less likely to be preserved.

To spread knowledge on how to adapt traditional Lebanese houses for modern living by enhancing thermal comfort, optimizing passive design strategies, and minimizing the use of non-renewable energy sources, making restoration a more viable and appealing choice.

1 European Union (MEDA Programme) and Antoine Fischfisch, Douma – CORPUS – Euromed Heritage (Euromed Heritage Programme, MEDA (European Union), 2003).

Target Audience and Relevance

This research is first handedly intended for architects, engineers and anyone involved in the building sector of Lebanon who have a responsibility in safeguarding the country's architectural heritage while advancing sustainable and energy-efficient practices.

It is also relevant for policy makers that are taking decisions on the preservation of built heritage on the Lebanese territory, as well as the academic community and cultural heritage institutions whether public or private. By providing a comparative analysis and retrofitting solutions of a typical traditional house, the work supports the efforts in recognizing these houses as part of our cultural heritage and advocating for the establishment of official restoration guidelines within a legal framework.

Ultimately, this research is dedicated to Lebanese house owners and potential investors, to highlight the value of these houses and encourage their preservation as part of our cultural identity.

02 BACKGROUND AND CONTEXT

2.1 HISTORY AND DEVELOPMENT OF THE TRADITIONAL HOUSE

The Lebanese traditional house is the product of multiple factors that lead to its development and expansion throughout the territory. Geography, climate, socio-economic and environmental condition, foreign influences, and material availability all shaped the built heritage of Lebanon.

According to Friedrich Ragette, four distinct typologies can be distinguished and are further detailed in Table 2.1.1: [2]

1- The **Closed Rectangular House,** which is the most basic type, an open space under a flat roof that often combined living and animal space;

2- The **Gallery House:** characterized by a covered outdoor gallery or Riwaq with arches and columns, that serves as circulation and transition between interior rooms and the outdoor space;

3- The **Liwan** and **Courtyard House**, both houses that are organized around a vaulted hall open on one side (Liwan) or a central courtyard with a fountain and garden;

4- The **Central Hall House**, the most distinctive Lebanese type, with a central reception hall (dar) and triple-arched facade, surrounded by asymmetrically arranged rooms.

The history of Lebanon can help us trace this development. The first settlements were around 200,000 years ago during the stone age, but the first historical inhabitants were the semitic Canaanites, who later merged with sea travelers that were known as the Phoenicians, who established prosperous coastal cities and colonies all across the Mediterranean and Northern Africa.

Starting 814 BC with the founding of Carthage, the Phoenicians expanded their influence in the West of the Mediterranean and remained independent until their defeat by Alexander the Great. Hellenistic and Roman periods were times of flourishing trades, which consequently brought urban growth and architecture influence.

Up until the 7th century, the Byzantine rule had almost completely Christianized the country, but the later Omayyad rulers pushed the Christian minorities into the mountains, marking a plateau for the urban development and the spread of settlements.
Under the Crusaders, Mamluks, and later Ottomans, Lebanon became a refuge and crossroads between East and West.

Particularly under the Ma'ani and the Chehabi dynasties

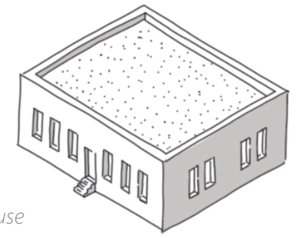
2 Friedrich Ragette, Architecture in Lebanon: The Lebanese House during the Eighteenth and Nineteenth Centuries (Caravan Books, 1980).

3 UN-Habitat, Lebanon Urban Profile (United Nations Human Settlements Programme (UN-HABITAT), 2011), www.unhabitat.org.

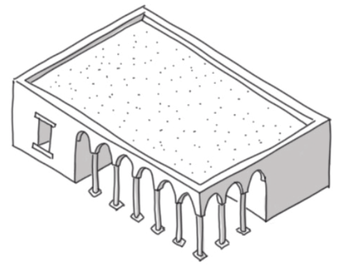
4 Ragette, Architecture in Lebanon: The Lebanese House during the Eighteenth and Nineteenth Centuries.

Figure 2.1.1 - Five Typologies of Traditionsl Lebanese Houses

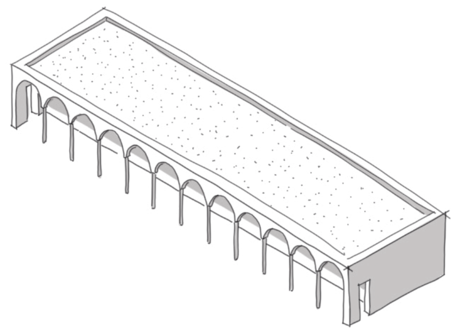
Source: Author's elaboration



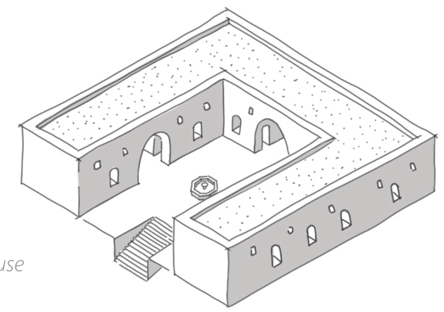
Closed Rectangular House



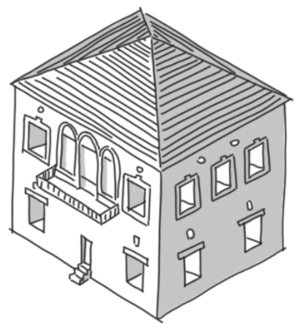
Gallery House



Liwan House



Courtyard House



Central Hall House

during Ottoman rule, trade and silk production with Florence, Venice and France flourished, and education and agriculture were improved by the 18th-19th centuries. Lebanese domestic architecture had then reached its characteristic forms.

The french influence in the 19th century reinforced cultural exchanges, eventually leading to independence in 1944.

Historically, the habitations were majorly on the coast, and the mountains provided timber for the building of ships during the Phoenicians era. Over time, the mountains developed into a recreational area, with seasonal homes still common today.

Currently, the urban population In Lebanon constitutes 90% of the total population[3], a figure that underscores the country's continued focus on coastal settlement pattern.

The Central Hall House, described by Friedrich Ragette as the Lebanese house "par excellence", typically has two floors: a ground floor and an upper first floor connected by an exterior staircase[4].

The first floor contains the central hall or "dar" which is the main living room with the typical triple-arch window and balcony. The rooms all open onto the "dar" and are organized around it, making it the central meeting space for the occupants. The ground floor often had a different layout and use than the first floor: the upper floor was usually where the main living area was because of its important exposure to sunlight and views, as well as to avoid the moisture from the lower floor. The ground floor was most frequently used as storage spaces, stable for animals, summer rooms for when temperatures were too high on the upper floor and could also serve as a secondary kitchen.

In terms of construction, the ground floor served a structural role in the house, with its stone walls limiting both the size and frequency of window openings. In addition, the thick walls helped retain heat in winter and kept the interior cool in the hot months, and the high ceilings helped keep the space cool in summer. The classic red-tiled "tarboush" roof of those homes had no chimney stacks built-in as they were not part of the original design.[5] Heating was either nonexistent or was provided by portable devices and open fireplaces such as the "Kenoun" or the "Hharounn" – a cavity in the floor filled with hot coals to warm the room.[6] Families would burn charcoal, wood shavings and other biomass leftover to radiate heat, and would traditionally gather in one room around the brazier for warmth if the night was too cold.

In the early-mid 20th century, cast-iron stove known locally as "sobia" became increasingly common in Lebanese houses. Originally, they would be fueled by wood, but nowadays the modern version that provides strong heat requires diesel and a pipe for exhaust. The enclosed fire allows for cooking and channels the smoke through a chimney pipe, making it less harmful than an open fire.[7]

In central hall houses, the "sobia" was typically placed in the main room of the first floor which was used as a winter room and was the most central space in the house, providing warmth to all the surrounding rooms. In a two-story house with no internal stairs, only the occupied floor had to be heated, leaving the ground floor for storage or animals, and in the summer would be reconverted into a habitable space used for its cool environment. The centrality of the "dar" was beneficial for the entire floor, as leaving the bedroom doors open allowed the stove's radiant heat to warm the surrounding spaces.

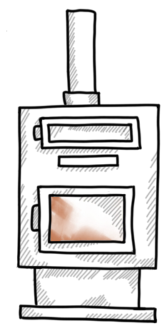


Figure 2.1.2 - Drawing of a Traditional Sobia Stove

Source: Author's elaboration

5 Nathalie Chahine and Fadlallah Dagher, eds., Houses of Beirut 1860-1925: Restoration Manual, Cahiers d'architecture (Beirut Heritage Initiative, 2021).

6 "Souk El Tayeb," Souk El Tayeb, https://www.soukeltayeb.com/.

7 "Syria Refugees Suffer Bitter Cold of Lebanon Winter," Arab News, accessed July 1, 2025, https://www.arabnews.com/node/680021/%7B%7B.

Since the Lebanese houses were not originally built with chimneys[8], heating came with its challenges for smoke exhaust. Historically, if only the portable brazier "Kenoun" was used, the window was kept slightly ajar for ventilation. However, the "sobia" has a sheet-metal pipe that runs vertically through the ceiling and the red-tiled roof to expel the smoke. Homeowners would remove or cut a clay tile to create an opening where the pipe would extend high enough to ensure draft. This improvised solution comes with challenges such as water leakage, air infiltration, and sometimes smoke leakage inside the house. Similarly, if the "sobia" was positioned at the side of the house, an opening would be cut in the wall, and the pipe would run along one of the secondary façades.

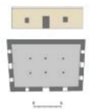
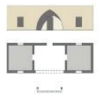
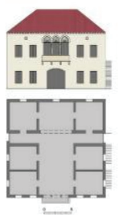
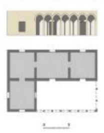
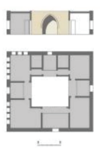
The following Table 2.1.1 is a detailed description of each typology of traditional Lebanese houses according to Friedrich Ragette's Architecture in Lebanon, and helps us understand the main differences and similarities between each of them.

8 Chahine and Dagher, Houses of Beirut 1860-1925.

Table 2.1.1 - Comparison Table of the Five Typologies of Traditional Lebanese Houses (Continued on next page)

Source: Author's elaboration based on Ragette (1980)[4]

Table 2.1.1
(Continued)

	PLAN FACADE	DATE	EVOLUTION - HISTORY	PLAN DESCRIPTION
RECTANGULAR HOUSE		· 5000 BC – First traces of dwellings with rectangular, circular, and trapezoidal shapes. 3200–3100 BC – · Emergence of more organized rectangular monocellular houses. 1500 BC – Canaanite houses: rectangular, built with clay or brick · dried slowly, bound with clay mortar on stone foundations.	· Early forms – Built in mud and rubble. Later – Transition to cut-stone construction. · Arches introduced – Dividing spaces both horizontally in plan and vertically in section.	· Form – Single open rectangular or square space. Use – All functions (working and living) grouped into one space. · Innovation – Introduction of arches allowed vertical separation between living and service areas.
CROSS-VAULTED RECTANGULAR HOUSE				· Structure – Two cross-vaults of 36 m² each. · Circulation – Staircase begins on the ground floor, turns around the corner of the house, and continues up to the roof.
GALLERY HOUSE (RIWAQ)		· 4th–6th century AD - Byzantine influence on settlement and building forms. · 16th–19th century – Further development and evolution of house types during the Ottoman period.	· Extensions – Added only when the need arose. · Multifunctionality – Instead of built-in furniture, different functions were assigned to separate rooms or floors.	· Riwaq – Open space connected to the outside by columns. Interior Layout: Can be a large open space with multiple doors to the gallery or a divided interior. · Plan: Symmetrical (common in Lebanese homes) or asymmetrical. · Gallery – Can wrap around the corner of the house, and may be present on both floors. · Functions – Reception/guest areas placed opposite to the family areas, usually near the entrance or on the upper floors.
CENTRAL HALL HOUSE (TRIPLE ARCH HOUSE)		· 14th–15th century – Venetian and Istrian houses show similarities with the central hall house. 18th–19th century · – Central hall house emerges, evolving from earlier Liwan and courtyard house traditions.	· Considered the Lebanese house par excellence. When more space was needed, an extra wing or extension, often with corridors, was added. Two central hall groups are rare, as · each generation typically built its own house. In the late 19th century, Western influence made the central hall · plan the most popular, transforming houses into formal villas called "harat" (plural of hara).	· Most central hall houses have two floors (81%) and are often built on slopes with hillside access (59%). They commonly feature a triple arcade (88%) and a symmetrical plan (85%). · The main floor usually has a single entrance (81%), from the rear (41%) or side via a corridor (33%). · Multi-access (19%) and three-storey houses (8%) are rare. In side-entry houses, symmetry is maintained by corridors. · Triple arcades are typically not used as entrances, except in some urban cases on the ground floor.
LIWAN HOUSE		· 3000–2800 BC – Origins traced to Persia. · After 7th century AD – Introduced to Lebanon by the Arabs.	· The least common house type in Lebanon, suited for warm climates. · The Liwan is oriented towards the hill, creating an upper terrace with living quarters above and service areas below. · Today, most have replaced the original timber roofs with reinforced concrete slabs.	· Liwan – Central space connecting two closed rooms on the right and left. · Functions as a covered terrace: protects from wind, dust, animals, and people. · Serves as both a connecting zone and a reception/living area for the family.
COURTYARD HOUSE		· 18th century – Became significant in Lebanon, especially in aristocratic residences.	· Origin – Liwan + side rooms linked to an open courtyard/terrace. · Adaptation – On slopes, liwan raised above ground with service floor below. · Shift – Entry reversed; liwan became an interiorized space. · Evolution – Large arch replaced by triple arcade with door + balcony. · Result – Courtyard–liwan scheme evolved into the Central Hall House.	· Central courtyard with rooms arranged around it.

	SPACE DIVISION	MAIN ENTRANCE	EXTERIOR WALL MATERIALS	EXTERIOR WALL DIMENTIONS	FOUNDATION
RECTANGULAR HOUSE	· Interior layout – Floor sometimes raised in specific areas to create divisions without partitions. · Kitchen & stove – Placed on the northern side outdoors, often with a “tannur” oven and a “bir” water reservoir.	· Entrance – Marked by a low door (“bab”). Shading – Space in front of the entrance often shaded by a tree or vine leaves. · Clusters – Can be part of a group of houses sharing a common courtyard (“hosh”).	· Structure – Stone load-bearing walls. · Composition – Built in three sections: · Exterior leaf of roughly cut stones (picked from the ground), interior leaf of the same, and core fill of rubble in between.	· Wall thickness – 50–100 cm, often with storage niches. · Layers – Exterior 35 cm, core 40 cm, interior 25 cm with 4–5 cm lime plaster.	· Foundations – Carried to bedrock when possible, at least 1 m below ground. · Made of compacted loam and stones.
CROSS-VAULTED RECTANGULAR HOUSE			· Structure – Stone load-bearing walls with vaults on the ground floor supporting the upper floor.	· Wall panels – 40–50 cm thick.	
GALLERY HOUSE (RIWAQ)	· Gallery – Can be passive (open sitting space) or active (used for circulation and distribution). · Two-storey layout – Service and living areas are usually separated vertically between the two floors. · Kitchen & sanitary rooms – Located in the service area or outside; in city houses often placed in annexes.	· Access – From the open surroundings. · Front stairs – Entry often from the front through stairs, positioned opposite the slope. · Interior access – Main entry is through the gallery.	· Gallery – Row of stone pillar posts. · Walls – Ashlar masonry, usually plastered.	· Wall thickness – 50–100 cm, often with storage niches. · Layers – Exterior 35 cm, core 40 cm, interior 25 cm with 4–5 cm lime plaster.	· Structure - Ground floor with stone pillars and vaults, upper floors with arcades of pointed arches.
CENTRAL HALL HOUSE (TRIPLE ARCH HOUSE)	· Layout – Houses range from 1 to 7 rooms on a single floor. · Urban Houses – Built centrally on the plot, with façades of equal importance; ground floor often used as a dwelling. · Floors – Each floor is an independent apartment with external staircase access. Rural Houses: Service areas (toilet, kitchen) often in the garden. · Distribution – Upper floors are symmetrical · Ground Floor Vaults – Often open, used for work or storage.	· Entrance – Usually from the front, main façade.	· Material– Primarily stone, with few exceptions. · Sandstone Density– Varies by façade orientation (e.g., dense limestone on rain-exposed walls, softer sandstone elsewhere). · Finishes – Rock-faced masonry on lower floors, smoother finish on upper floors.		· Foundations – Carried to bedrock when possible, at least 1 m below ground. · Made of compacted loam and stones.
LIWAN HOUSE	· Stables & storage rooms – Usually built separately. On sloping terrain, sometimes placed behind the liwan at a different level or under the liwan. · Side rooms – Directly connected to the liwan, which itself is linked to the external space in front.	· Entrance – From the side or rear.	· Material - Stone		· Bearing walls – Two ashlar stone faces with rubble core, 60-100 cm thick. · Stone size – Height 25-35 cm, length 25-50 cm, thickness 20-30 cm.
COURTYARD HOUSE	· Up to three liwan units framing the courtyard, with living and service spaces in surrounding wings.	· Main entrance – Usually from the side or rear, never from the valley side on slopes.	· Exterior wall materials – Primarily stone masonry, sometimes plastered.		· On sloping ground, wings may rest on large vaults opening to the exterior.

Table 2.1.1
(Continued)

	ROOF	ROOF MATERIALS	ROOF DIMENTIONS	INDOOR PARTITIONS MATERIALS
RECTANGULAR HOUSE	· Flat earth roof, used as a working surface in the dry season (e.g., drying fruits, cereals, etc.).	· Flat beam construction. · Earth, branches and stones.	· 10–20 cm timber beams at 20–40 cm centers · Reeds or branches 5 cm shrubs in moist earth · 20–25 cm dry earth · 4 cm stone chips · 2 cm lime–chaff screed, flattened with a stone roller	· Non-existant
CROSS-VAULTED RECTANGULAR HOUSE	· Ground floor – Vaulted, supporting the first floor. · Roof – Flat earth, same as regular houses.	· Flat beam construction. Earth, branches and stones · Stone vaults on the GF.		· Vaults separate the spaces
GALLERY HOUSE (RIWAQ)	· Flat earth roof with timber structure, like the rectangular house, extended 3 m on external posts. · Variants – Some with tiled roofs (19th century).	· Flat beam construction. · Earth, branches and stones.		· Non-bearing walls & ceilings – Built with wood lath and plaster, similar to plastered reed construction.
CENTRAL HALL HOUSE (TRIPLE ARCH HOUSE)	· Tiled roof with red terracotta tiles and timber structure. · Attic – Typically uninhabited.	· Top floor – Never vaulted (too heavy and costly). · Flat roof – Width too limited to support full house construction. · Roof structure – Cut timber framework covered with red tiles.	· Red clay tiled roof on a timber structure.	
LIWAN HOUSE	· Flat timber and earth construction. · Tiled roofs – Rare, due to the age of the houses and their irregular plans.	· Flat beam construction. · Earth, branches and stones.	· 10–20 cm timber beams at 20–40 cm centers · Reeds or branches 5 cm shrubs in moist earth · 20–25 cm dry earth 4 cm stone chips · 2 cm lime–chaff screed, flattened with a stone roller	· Mud brick partitions with niches and recesses.
COURTYARD HOUSE	· Flat or pitched depending on region, with occasional galleries above wings.	· Timber beams with earth cover; tiled roofs introduced later.		· Mostly stone walls, some mud-brick subdivisions with niches (like in liwan-related types).

RELATION WITH TERRAIN	ORIENTATION	STRUCTURE / SPAN	HEATING
· On sloping sites the ground floor becomes a half-basement on one side.	· As a rule the view is down the valley. · On flat terrain, main house facade is oriented west.	· Roof span limits – Determined by timber length, about 4.5 m (with 50 cm diameter timber). · Practical span – Due to heavy roof (≈50 cm wood + earth), spans are limited to 2.5–3.5 m.	· Traditionally by brazier (kenoun) · Fireplaces in larger houses. · Fuel - Dried up manure and wood.
· Hilly terrain of Lebanon favors the facades.		· Cross-vaults – Height 3–5 m, span 4–5 m.	
Two floors – The lower floor backs into the slope, while the first floor is raised above ground on all four sides.		· Interior supports – Wooden posts. · Arches – Rest on slender columns (2–3 m high, ~20 cm diameter). · Buttressing piers – About 60 cm thick at the base. · Arch spans – Vary 1.20–3.80 m, most common around 2.50 m. · Gallery height – Same as rooms, about 4–5 m.	
Basements – Full basements are rare, but half-basements are frequent on sloping terrain.		· Interior supports – Wooden posts. · Arches – Rest on slender columns (2–3 m high, ~20 cm diameter). · Buttressing piers – About 60 cm thick at the base. · Arch spans – Vary 1.20–3.80 m, most common around 2.50 m. · Gallery height – Same as rooms, about 4–5 m.	
· Location– Free-standing units on mountain terraces of Lebanon. · Orientation – As a rule, the view is directed down the valley (see p.72 for layout diagrams).		· Liwan < 4 m – Beams run parallel to the arch, carrying the load (arches not load-bearing). · Liwan > 4 m – Several arches span across the liwan, beams run parallel to its depth. · Other rooms – Usually vaulted. · Hillside houses – Use of barrel vaults parallel to the contours, opening to the view or courtyard.	
· Common on slopes, with one side opening to view, others into the hill.	· As a rule the view is down the valley.	· Large wings carried by vaults, courtyards framed by arcades.	

Table 2.1.1
(Continued)

	WINDOWS / VENTILATION	TYPICAL FLOOR COUNT	ROOF DIMENTIONS	SPECIAL ELEMENTS	VARIATIONS
RECTANGULAR HOUSE	· Openings – Few, small windows. · Ventilation – Small openings called “taqat”. Typically one or two small windows only.	· 1 or 2 levels.	· Typically about 20 m², limited by span constraints.	-	· Beqaa Valley – Mud brick houses with walls about 80 cm thick, often plastered so they appear like stone houses.
CROSS-VAULTED RECTANGULAR HOUSE			· Vaulted rooms – About 36 m² per vault.		· North Lebanon – Single-floor cross-vaulted buildings are typical.
GALLERY HOUSE (RIWAQ)	· Ground floor – Stone pillars with arcades (pointed arches). · Ventilation – Through windows and doors.	· 1 or 2 levels. · Two-storey type is typical in Lebanese hillside settings.	· Small cells – Typically 10–15 m².	· Hybrid type – Mix of gallery and central hall house, where the gallery acts as a continuous balcony and sun shelter.	· Arcades – Sometimes continue around corners. · Commercial use – Gallery opens to the street; interior has no windows; gallery serves as public traffic area. · Residential use – Gallery functions as circulation and distribution space for residents.
CENTRAL HALL HOUSE (TRIPLE ARCH HOUSE)	· Ventilation – Through small openings (taqat) and windows.	· Floors – Range from 1 to 3 levels. · Most common – Two floors (≈80% of cases, Ragette’s survey).	· Shape – Square to rectangular. · Size – Usually ~20 m², rarely <4 m wide. · Central hall width – 3–6 m, most often 4–5 m. · Length – 3.5–12 m; longer halls often divided by an interior arcade.	· Hybrid forms – Gallery on GF with central hall above; or a Central Hall over a Liwan floor. · Materials – Sandstone walls, with limestone for structural/decorative elements (lintels, jambs, consoles, arches). · Balconies – Marble slabs (5 cm) on stone corbels, spanning up to 2 m; larger spans use galleries or projecting vaults.	· Plaster finish – Introduced at the end of the 19th century to allow use of porous local sandstone.
LIWAN HOUSE	· Apertures – Up to 80 cm, closed with stone lintels. · Larger spans – Use segmental, pointed, or decorative arches. · Liwan arches – Rarely semicircular; usually pointed with a horseshoe extension.	· Floors – Usually one storey. In some cases, a second level is added, with the · Liwan on the upper floor opening to a terrace on the hillside	· Liwan – About 3 m wide and 5 m deep. · Side rooms – Typically 4 × 4 m².	· Features – Benches and fountain often included. · Hybrid form – Central Hall unit above a Liwan floor.	· Linear extensions – Liwan units stretched by multiple rooms along the contours of the land. · Variations with gallery or multi-liwan units (sometimes cross-shaped). · View-oriented type – Liwan opens to the view with colonette + flower basin, rear window of normal size.
COURTYARD HOUSE	· Valley side with many windows; hillside side with small ventilation openings.	· Mostly two storeys, sometimes with vaulted basements.	· Liwan rooms dimensions. · Courtyards ≈15×15 m (larger houses), smaller examples ≈25 m² courts.	· Central fountain, benches at entrances, bath complexes in larger palatial types.	· 3 liwans around a courtyard with fountain (Islamic influence, Deir el Qamar). · Terraced types – Overlapping houses on slopes. · View-oriented type – Courtyard faces the view; entrance from side or rear. · Open terrace type – Valley side removed. · Gallery-wing type – Arcaded wings like a gallery house.

The Central Hall House is not only a distinctive architectural form but also an embodiment of vernacular architecture and climate-responsive design that answers to Lebanon's Mediterranean climate. Several features demonstrate it: [9]

1 Orientation: Houses were typically oriented towards the valley or, along the coast, towards the sea on the west. This ensured access to prevailing breezes, optimal views and passive solar exposure.

2 Ventilation: Small high-level openings known as "taqat" combined with low windows and the high ceilings, created a natural stack effect, enhancing cross-ventilation and passive cooling in the summer.

3 Thermal Inertia: The thick local stone walls and terracotta tiled roof absorbed heat during the day, delaying its transfer to the interior, and gradually releasing it at night.

4 Shutters: Wooden exterior shutters provided flexible exterior solar control, blocking excess sun and heat.

5 Shading and Greenery: Shaded front entrance porch often framed by grapevines pergolas, usually paired with a rear courtyard planted with trees and fountains, cooled the air and provided shading.

6 Outdoor Spaces: Typical Lebanese garden with fruit trees and water features cooled the air through evaporation, extending the comfort zone outdoors and integrating the microclimatic regulation into the house.

7 Triple Arcades: The iconic three-arched facade is not only aesthetic, it also enhances natural ventilation in summer and maximized passive solar gains in winter, as well as increased natural daylight in the central hall.

These environmental strategies highlight the Central Hall House as a climate responsive structure. Its design is a result of centuries of experience in balancing comfort with the Lebanese hot summers, cool winters, and diverse topography.

9 Ragette, *Architecture in Lebanon.*

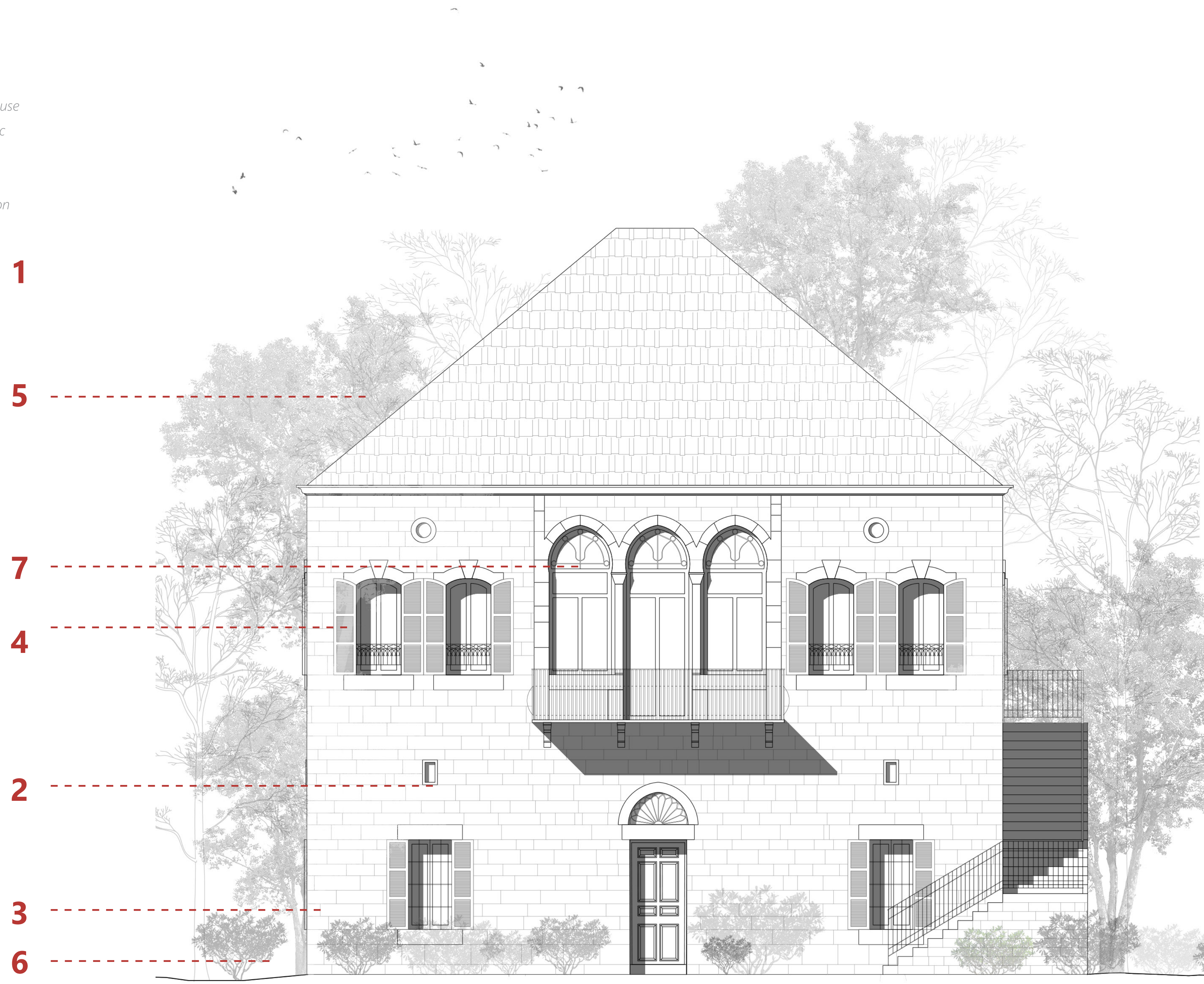


Figure 2.1.3 - Lebanese House West Facade: Characteristic Features 1/100

Source: Author's elaboration

Figure 2.1.4 - Lebanese House South Facade 1/100

Source: Author's elaboration

Figure 2.1.4 - Lebanese House North Facade 1/100

Source: Author's elaboration

2.2 BUILDING PRESERVATION AND LEGISLATION

2.2.1 LEGAL FRAMEWORKS

To begin the research, it is important to require insight into the laws governing heritage conservation practices in Lebanon, as well as an understanding of the ethical considerations involved in restoring traditional houses to be able to set a first limit to the future interventions.

The Lebanese "Direction Générale des Antiquités" (DGA) put in place laws for the protection of heritage which never took effect. The first attempt to put this law into effect happened in 2007 with the creation of the law on the preservation of archeological and heritage buildings, which was approved but never put into effect. A second attempt at passing this law took place in 2017, which led to it being approved.[10]

Numerous heritage laws and legal frameworks have been implemented such as the Law No. 35/2008 which affects the organization of the Ministry of Culture, restructuring the ministry to develop cultural policies, protect archaeological sites, traditional architecture, and heritage buildings and put in place a heritage fund.[11]

Another interesting law to cite is the Law No. 37/2008, focusing on cultural property. The latter introduces the "cultural property" status for both intangible and tangible heritage and advocates the implementation of emergency protective measures and civil society engagement. [12]

Moreover, the government issued the 1933 Antiquities Law and 1942 Decree, a regulatory measure which applies only to structures built before 1700, imposing prior approval for modifications made to these structures (Article 12), as well as allowing imposing servitudes to preserve heritage (Article 27). [13]

However, despite the existence of these laws, their implementation remains largely absent in practice. The legal framework, while present on paper, is undermined by the lack of concrete guidelines, enforcement mechanisms, and governmental commitment. Thus, these measures often fail to transform into actionable practices despite efforts made to establish a structured legal response facing the issue. This causes the law to be supplanted by a combination of voluntary guidelines, strategic action plans and Non-Governmental Organization interventions.[14]

10 Khaled Abdulsalam, The Legal Protection of the Cultural Heritage Under the Lebanese Law, n.d.

11 Salpy Nalbandian, "LibGuides: Beirut's Heritage Buildings: Resolution 166 (Antiquities Law)," accessed January 16, 2025, https://aub.edu.lb.libguides.com/c.php?g=1090674&p=7977619.

12 European Union (MEDA Programme) and Antoine Fischfisch, Douma – CORPUS – Euromed Heritage.

13 Nalbandian, "LibGuides."

14 Silvia Mazzetto, Sustainable Reuse of Heritage in the Middle East Constrained Environments (2021), 63–91, https://doi.org/10.1007/978-981-33-4631-4_5.

15 Chahine and Dagher, Houses of Beirut 1860-1925.

16 Abdulsalam, The Legal Protection of the Cultural Heritage Under the Lebanese Law; Nalbandian, "LibGuides."

17 Silvia Mazzetto, "Lebanese Heritage: Preserving Values to Build Identity," Proceedings of International Structural Engineering and Construction 7 (August 2020), https://doi.org/10.14455/ISEC.res.2020.7(1).AAE-12; CORPUS – Euromed Heritage, Traditional Mediterranean Architecture (MEDA programme of the European Union, 2003).

18 Order of Engineers and Architects of Beirut; LIBNOR; ECOTECH Engineering; ADEME; ALMEE; ASHRAE Lebanese Chapter; LGBC, Thermal Standard for Buildings in Lebanon (TSBL), Bulletin de l'Association Libanaise pour la Maîtrise de l'Energie et l'Environnement (ALMEE), 2010.

On this note, all traditional Lebanese houses built after the 1700 have no laws put into place to protect them, suggesting a legal gap as many buildings fall outside the scope of the Antiquities Law.[15]

We can name a few reasons as to why these laws remain largely non-operational. Chief among these is the absence of executive decrees, as well as limited financial resources and weak mechanisms for their enforcement. The Ministry of Culture, being legally responsible for monitoring heritage preservation, remains significantly under-resourced thus limiting its impact. On the other hand, municipalities are positioned closer to local communities and operate on independent budgets. However, their involvement and scope of activity varies considerably from one municipality to another, depending on local priorities and political circumstances.[16]

Consequently, individuals, private initiatives, and non-governmental organizations (NGOs) are nowadays taking the lead in restoration efforts as the burden falls onto them. Due to the absence of a sustainable national heritage protection plan, an implied ethical responsibility is placed on the local communities to protect cultural heritage in the face of institutional gaps.[17]

One organization which tackled this issue is the Order of Engineers and Architects of Beirut.

According to the Order of Engineers and Architects of Beirut (OEA), Lebanon currently lacks clear and enforceable guidelines for thermal performance in building envelopes. To fill in this regulatory gap, the Thermal Standard for Buildings in Lebanon (TSBL) was established for new constructions to provide a reference framework. However, the question to be raised would be the potential applicability of this standard to heritage buildings (further discussed in Section 4.5).

Keeping in mind that the TSBL is one of the few national guidelines addressing energy efficiency in the building sector in Lebanon, adapting it for traditional houses could represent a significant step toward improving the energy performance of Lebanon's architectural heritage.[18]

Table 2.2.1.1 - Thermal Transmittance Requirements for Lebanese Residential Buildings according to the TSBL

Source: Author's elaboration based on the TSBL

ROOF	**U-values (W/m².K)**	0.63
WALL		0.77
WINDOWS		4.00
GF SLAB		0.77*
		1.20**

**Exposed*
***Semi-Exposed (in contact with non-air-conditioned space)*

2.2.2 CURRENT RETROFITTING PRACTICES

Retrofitting practices as we can see in Beirut's historic homes aim to balance structural rehabilitation with respect for architectural heritage. This practice, mainly focusing on Lebanese houses constructed between 1860 and 1925 has gained prominence amongst growing awareness of heritage preservation and the functional demands of contemporary living.

Chahine and Dagher's study of Houses of Beirut addresses the architectural integrity and cultural significance of these buildings, highlighting the challenges and strategies that are currently employed in retrofitting efforts. [19]

The houses of this period presented unique structural and aesthetic considerations such as triple-arched windows, red-tiled roofs, and thick masonry walls. It is thus through retrofitting practices nowadays that the architectural identity of these homes is preserved while adapting them to modern standards of comfort, safety and sustainability.

One interesting method argued in the book is the reinforcement of load-bearing masonry walls using reversible and non-invasive methods. These methods include stitching with stainless steel, glass fiber, or carbon fiber bands, which improve seismic performance without compromising historic authenticity (Figures 2.1.2.1 - 2.1.2.2, and 2.1.2.3)

19 Chahine and Dagher, Houses of Beirut 1860-1925.

Figure 2.1.2.2 - New aluminium Shutters in a Traditional Style (Right)

Source: Author's elaboration

(From Left to Right)

Figure 2.1.2.1 - IP Cracks Stitching Technique: Plaster around cracks stripped (Left)

Figure 2.1.2.2 - IP Cracks Stitching Technique: U shape stainless steel 316 L flat strips introduced inside the joints (Middle)

Figure 2.1.2.3 - IP Cracks Stitching Technique: Structural mesh installation (Right)

Source: Chalhoub, M. et al. (2021). Houses of Beirut 1860–1925: Restoration Manual, p. 43

In parallel, window and door openings are also conserved through the implementation of custom-made replacements if lost of heavily damaged, which are crafted using traditional carpentry methods.

In another example, roofing systems are often preserved using traditional carpentry techniques and reinforcements where needed using cutting and displacement, while red tiles are cleaned and preserved.

(From Top to Bottom, Left to Right)

Figure 2.1.2.4 - Traditional Door with Rectangular Frame and Double Leaf

Source: Author's elaboration

Figure 2.1.2.5 - Window with Shutters on the Ground Floor

Figure 2.1.2.6 - Disruption in Roof Structure: Purlin Flexion and Rafter Misalignment

Figure 2.1.2.7 - Cutting and Displacement Technique: Overlapping New Piece for Extra Length

Figure 2.1.2.8 - Damaged tiles in the aftermath of the August 4th blast

Source: Chalhoub, M. et al. (2021). Houses of Beirut 1860–1925: Restoration Manual, p. 43

Nowadays, retrofitting projects in Beirut have pivoted from purely technical restoration projects to a multidisciplinary intervention which requires collaboration among architects, artisans, and heritage experts to make sure that these interventions remain considerate of both the material and intangible values of the original structures. Chahine and Dagher emphasize the importance of this collaborative ethos, particularly in a city where the built environment embodies layers of cultural and historical significance.

The retrofitting approaches utilized are more and more customized to the specificities of each building of Beirut, taking not only their constructional details into consideration but their role within the urban and social fabric of the city.

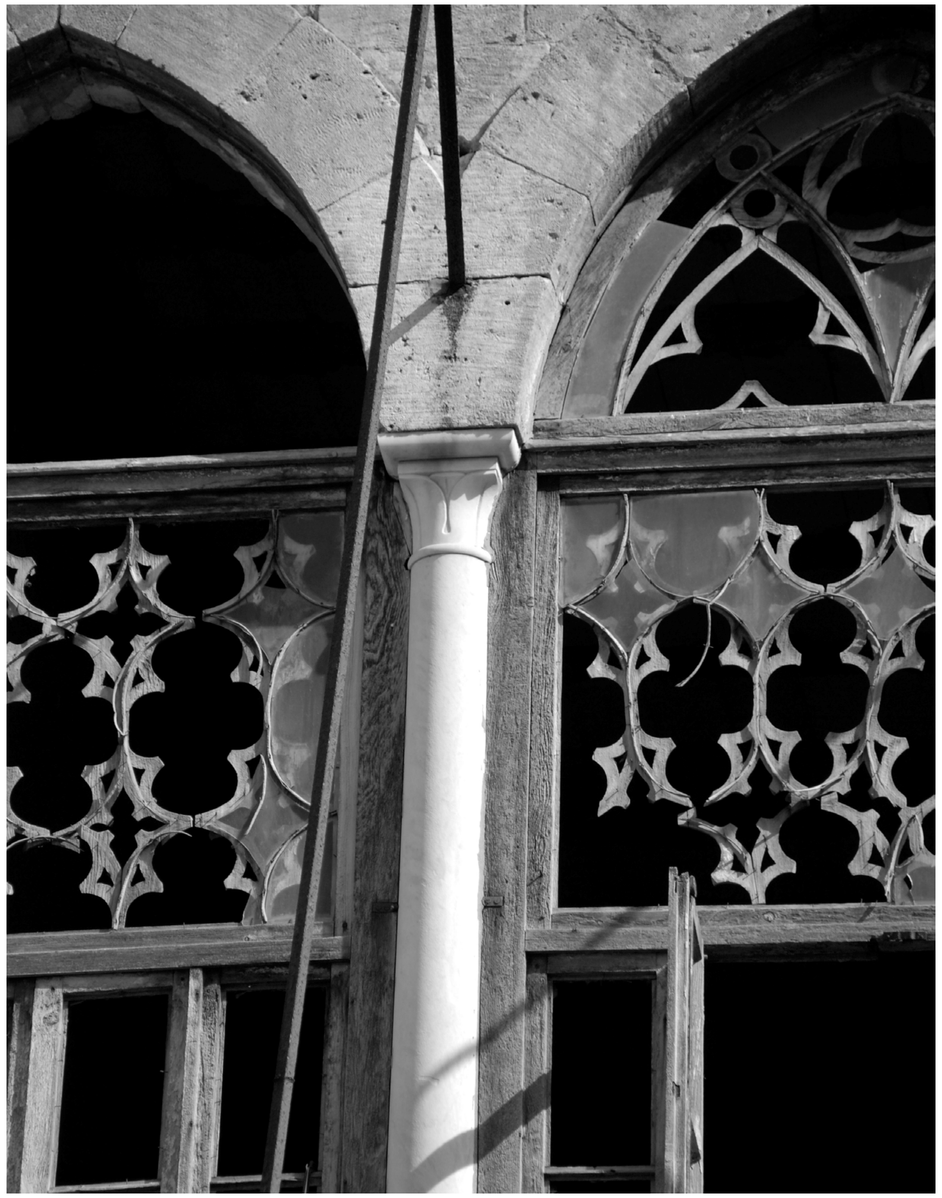


Figure 2.1.2.9 - Unrestored Triple Arch Window

Source: Author's elaboration

2.3 Lebanon's Energy Infrastructure and Use

2.3.1 ENERGY GRID AND DISTRIBUTION

Lebanon's energy grid is heavily reliant on imported fuel to produce energy, with 98% of primary energy supply sourced externally. Thermal power plants fueled by oil products make up 95% of the electricity generated for residential use, while the national grid Électricité du Liban (EDL) supplies just over half of the electricity demand for residential use - often inequitably distributed across different regions. The remaining demand is typically covered by privately owned diesel generators, which worsens social inequality due to their high operational costs, inflated black market rates for diesel, and the lack of effective government oversight on the kilowatt-hour price, taking advantage of fuel shortage and unreliable grid supply.[20]

Oil remains the dominant energy source, accounting for 86.2% of total energy supply in 2022 (Figure 2.3.1.1), although its consumption has declined in recent years due to economic crises and fuel scarcity (Figure 2.3.1.3). This led to a notable shift toward alternative energy sources, particularly solar photovoltaic (PV) panels (Figure 2.3.1.2), giving the households the ability to be as self-sufficient as possible. In 2022, solar PV alone accounted for 29.1% of domestic electricity production and 6% of household supply in 2023.[21]

Despite this growth, the domestically produced energy as a whole represents only 5% of the total energy supply, in contrast to the 86.2% dominated by imported oil (Figure 2.3.1.1). Within those 5%, renewable resources include 49.6% from solar, geothermal and wind, 17% from hydropower, and 33.4% for biofuels and waste (Figure 2.3.1.2). Although still modest, these figures highlight a potential growing contributor to decentralized and locally produced energy (Figure 2.3.1.5).[22]

In 2023, 92% of households had access to some electricity source, with 73% connected to the public grid. However, daily outages averaged 10 hours, leaving generators to cover 14 hours per day and solar-equipped households up to 18 hours. Since grid electricity is cheaper, households use it whenever available, meaning that the public grid accounted for 58% of the daily supply and diesel generators for 42%, calculated as 14/24 h and 10/24 h respectively (Figure 2.3.1.4).[23]

20 Nour Wehbe, "Optimization of Lebanon's Power Generation Scenarios to Meet the Electricity Demand by 2030," The Electricity Journal 33, no. 5 (2020): 106764.

21 International Energy Agency (IEA), "Lebanon - Electricity," International Energy Agency (IEA), 2024, https://www.iea.org/countries/lebanon/electricity.

22 International Energy Agency (IEA), "Lebanon - Electricity."

23 United Nations High Commissioner for Refugees (UNHCR) et al., VASyR 2023 – Vulnerability Assessment of Syrian Refugees in Lebanon: Thematic Energy Report (UNHCR; WFP; UNICEF, 2023), 127, https://reliefweb.int/report/lebanon/vasyr-2023-vulnerability-assessment-syrian-refugees-lebanon.

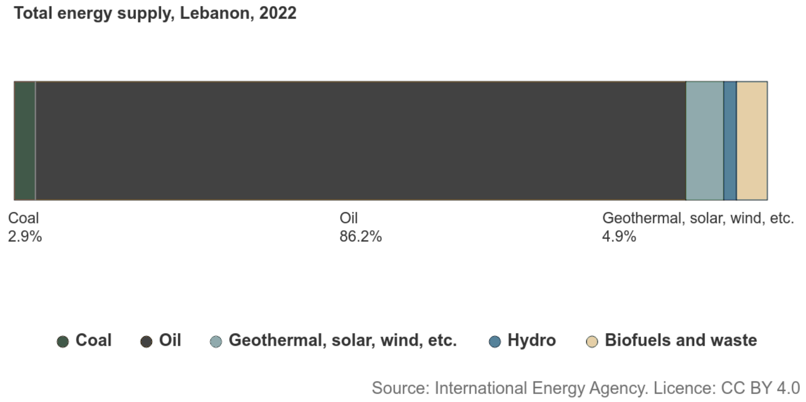


Figure 2.3.1.1 - Total Energy Supply, Lebanon, 2022 (IEA)

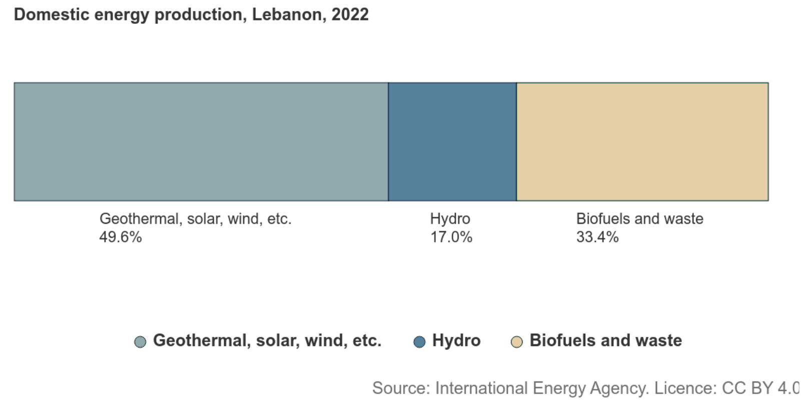


Figure 2.3.1.2 - Domestic Energy Production, Lebanon, 2022 (IEA)

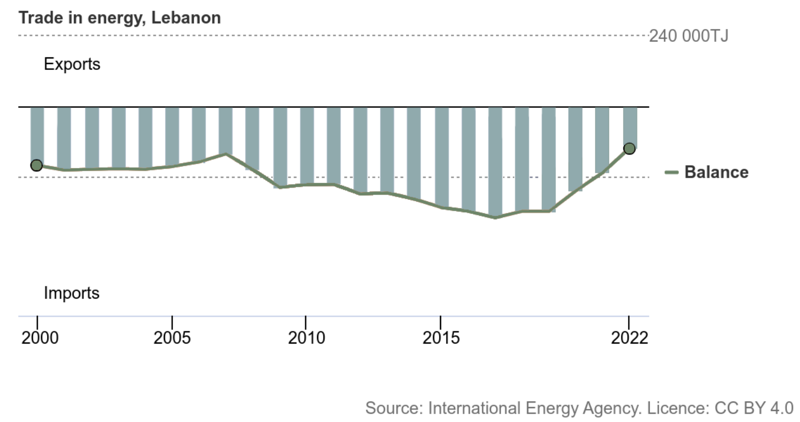


Figure 2.3.1.3 - Trade in Energy, Lebanon (IEA)

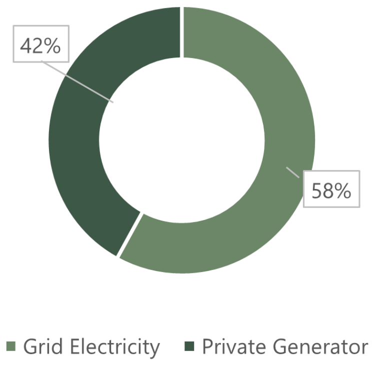


Figure 2.3.1.4 - Household Electricity Supply Sources

Source: Author's elaboration

To accurately evaluate energy performance, we first need to determine the Primary Energy Factor (PEF) for the Lebanese electricity mix. This value enables us to convert the Delivered Energy (DE) consumption into Primary Energy (PE), giving us a more accurate representation of the total upstream energy required to supply the household while incorporating the effects of generation losses, conversion inefficiencies and types of energy source used. It allows for a clearer assessment of the environmental impact and carbon intensity associated with electricity generation and consumption.[24]

According to the International Energy Agency (IEA), Lebanon's grid emission factor reached approximately 0.613 tCO2 per megawatt-hour (MWh) in 2022, indicating a fossil-fuel dominated electricity mix based on combustion. Furthermore, fuel combustion alone was responsible for 9.431 Mt CO2 in 2022, while the country's per capita CO2 emissions were estimated at 1.718 tCO2 in the same year.

Electricity and heat production has been the highest emitting sector in Lebanon since 2000, peaking at 16 million tons (Mt) of CO2 in 2019, and dramatically declining to 2 Mt CO2 in 2022 due to the economic and energy crisis which reduced electricity production by the national utility (EDL). Ultimately, the residential sector experienced a reduction with emissions dropping from 1 Mt CO2 in 2021 to 0.4 Mt CO2 in 2022, which can be attributed not to improved efficiency, but rather a reduced access to grid electricity, forcing many households to either reduce consumption or shift to informal and off-grid alternatives such as private generators and solar PV panels.[25]

Since there is no data for the primary energy factor (PEF) of Lebanon's grid electricity, this led us to calculate the hypothetical value based on information from sources such as the International Energy Agency IEA (Figure 2.3.1.7). Oil-fired thermal power plants typically operate with an efficiency of 35-40% which corresponds to a Primary Energy Factor – also known as a fuel factor – with an efficiency ranging from approximately 2.5 to 3. In comparison, Diesel generators operate at 25-30% efficiency and are associated with higher PEF values of around 3.3 to 4.

According to the EN ISO 52000-

24 International Energy Agency (IEA), "Lebanon - Electricity."

25 Ibid.

Figure 2.3.1.5 - Evolution of Domestic Energy Production in Lebanon since 2000 (IEA)

Figure 2.3.1.6 - Evolution of CO2 Emissions by Sector in Lebanon since 2000

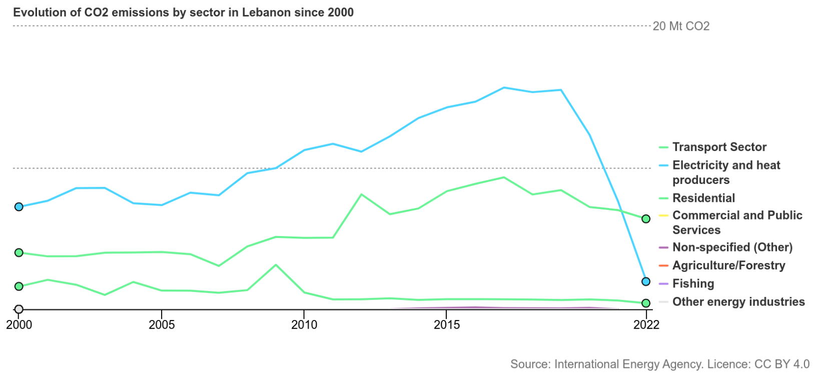
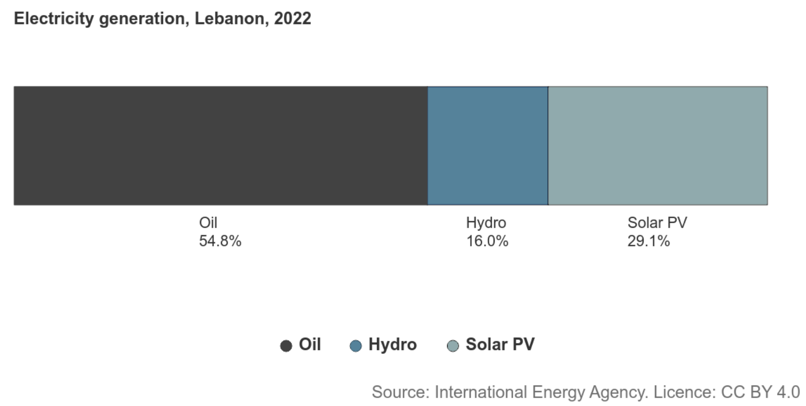


Figure 2.3.1.7 - Electricity Generation in Lebanon in 2022



1 Standard, the default PEF for renewable electricity is set to 1.0, while fossil-based electricity is typically 2.5 to 3.0, depending on the mix of energy sources used in the electricity production.

In the case of Lebanon, the International Energy Agency (IEA) states that electricity generation in 2022 was derived from approximately 54.8% oil combustion, 16% hydropower and 24.1% solar energy. Given the fossil fuel dominated mix, a weighted average PEF would need to be calculated to accurately represent the Lebanese electricity grid in energy performance analysis. [26]

The PEF of the public grid is then calculated using a standard efficiency of 35% with a PEF = 1.20 for oil, and a PEF = 1.00 for renewables [27] using the following formula: [28]

$$PEF = \frac{1}{Efficiency}$$

Oil (PEF = 1.20) fired electricity:

$$PEF = \frac{1}{35} = 2.86$$

The PEF for private diesel generators is calculated using a standard efficiency of 30% with a PEF = 1.1 for diesel.

Diesel (PEF = 1.10) generator:

$$PEF = \frac{1}{30} = 3.30$$

The PEF for Lebanon's electricity mix is the following:[29]

PEF hydro = 1.00
PEF solar[30]= 1.00

PEF electricity= Sum (Share x PEF)

= (54.8% x PEF oil) + (16% x PEF hydro) + (24.1% x PEF solar)

= (0.55 x 2.86)+(0.16 x 1)+(0.24 x 1)
= 1.57 + 0.16 + 0.24

PEF elec = 1.97

After determining a typical scenario of electricity sourcing of 58% from the national grid and 42% from diesel generators, we can estimate the PEF of the household electricity consumption.[31]

PEF mixed sourced elec
= (% grid x PEF grid) + (% gen x PEF gen)

= (0.58 x 1.97) + (0.42 x 3.3)

PEF mixed sourced elec = 2.53

The final PEF of Lebanon's electricity that reaches the residential is a mix of both the public grid and the private diesel generators.

While Lebanon remains highly dependent on imported fossil fuels - particularly oil - the recent rise in solar energy and the growing potential for domestic energy production denotes a positive trend towards achieving households' self-sufficiency and

26 Ibid.

27 International Organization for Standardization (ISO), Energy Performance of Buildings — Overarching EPB Assessment — Part 1: General Framework and Procedures, 2017, https://www.iso.org/standard/65601.html.

28 Anke Esser et al., Final Report — Evaluation of Primary Energy Factor Calculation Options for Electricity (European Commission, Directorate-General for Energy, 2016), https://energy.ec.europa.eu/system/files/2016-12/final_report_pef_eed_0.pdf.

29 International Organization for Standardization (ISO), Energy Performance of Buildings — Overarching EPB Assessment — Part 1: General Framework and Procedures. Section 5.2.3, Eq (2)

30 Ibid.

31 Ibid.

more sustainably sourced energy. In a small country plagued by unreliable electricity provision, frequent daily power cuts and high consumer costs, diversifying the energy mix and improving energy efficiency in buildings can help reduce reliance on volatile fossil fuels imports, ultimately strengthening local renewable energy production in order to boost energy security and reliance in the long term.

A comprehensive overview of these dynamics is illustrated in the Sankey diagram at the end of this section (Figure 2.3.1.8). [32], [33], [34]

This diagram's purpose is to show the flow of energy from primary source down to household end-uses, breaking down the share of electricity-dependent uses such as cooling, lighting, domestic hot water (DHW) and appliances, while separating heating as a distinct category. Unlike the other end-uses, heating is supplied mainly through direct combustion of renewable and non-renewable fuels such as biomas, diesel, gas and kerosene, with only a small fraction covered by electricity.

This distinction highlights the dual nature of Lebanon's household energy demand, one part tied to the reliability of the public grid, and on diverse direct fuel sources, depending on their availability and market price.

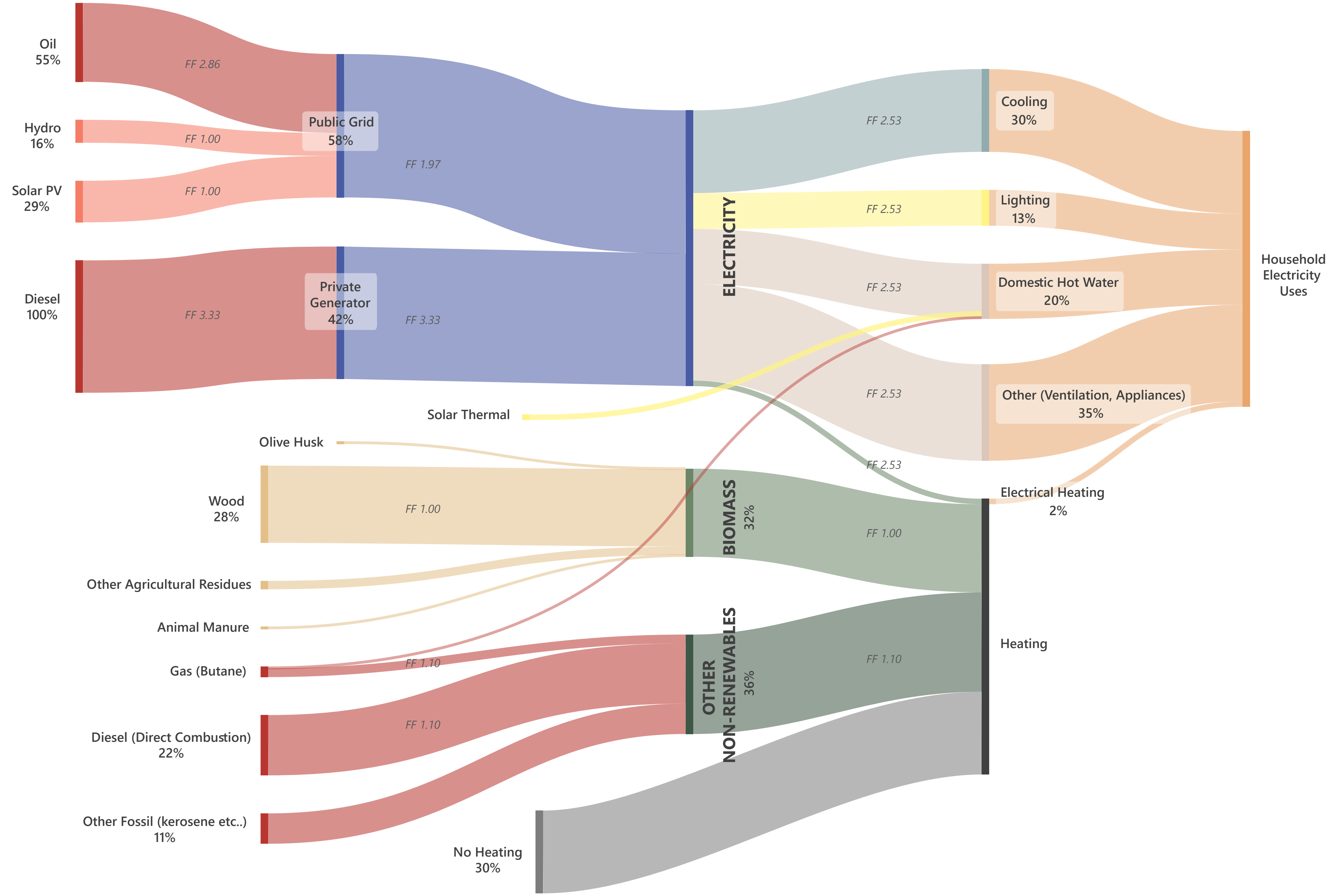
32 Dr. Sorina Mortada (Lead Author) et al., The First Energy Indicators: Report of the Republic of Lebanon (Lebanese Center for Energy Conservation (LCEC), 2018), 51, https://www.lcec.org.lb/sites/default/files/2021-02/Indicators%20Report_VF.pdf.

33 International Energy Agency (IEA), "Lebanon - Electricity."

34 S. Yathreb, "Analysis of a Residential Building Energy Consumption as 'Base Model' in Tripoli, Lebanon," International Journal of Energy Production and Management 1 (November 2016): 359–70, https://doi.org/10.2495/EQ-V1-N4-359-370.

Figure 2.3.1.10 - Sankey Diagram of Primary Energy Sources and Final Energy Uses in the Lebanese Residential Sector

Source: Author's elaboration based on different sources (Mortada et al. (2021) IEA, Yathred (2016)



2.3.2 RESIDENTIAL ENERGY USE PATTERNS

In order to understand the current situation and potential paths for residential energy use in Lebanon, the following table 2.3.2.1 presents a summary of the main energy sources used in households, categorized into solar, biomass, and non-renewable types. It underlines their respective usage, geographic distribution across the four bioclimatic zones, and key advantages and disadvantages in their use. This table 2.3.2.1 reveals a heavy reliance on non-renewables to produce energy, especially in diesel oil and electricity backed by private generators but also points to a high use of biomass to heat, predominantly wood. The use of biomass to heat remains a significant contributor in rural and mountainous regions, offering cost-effective and locally sourced solutions. However, this comes with challenges such as illegal wood-cutting and deforestation leading to destabilizing the already threatened flora and fauna. This comparative breakdown sheds the light on both the environmental and socioeconomic impact of the current residential energy practices and the opportunities to explore more resilient and sustainable solutions. [35], [36], [37]

In 2023, 92% of households in Lebanon had access to some electricity source, while the remaining 8% - primarily located in rural areas - lacked access. Among those with access, the distribution of electricity access in the residential sector showed in 2023 that 73% were connected to the national grid (EDL) although it did not guarantee continuous hours of supply.

The nationwide crisis impacted the supply from the national grid, which declined between 2021 and 2023, leading to an increased reliance on diesel generators, rising from 47% in 2022 to 50% in 2023, and on solar panels, growing from 1.2% in 2022 to 6% in 2023. On average, power outages amounted to 10 hours per day in 2023, compared to 15 hours in 2022 and 6.5 hours in 2021. Private generators compensated by supplying electricity for 13 hours per day, while the 6% of households equipped with solar panels benefited from 18 hours of energy per day.

In 2023, households received on average 14 hours of electricity per day from the public grid and relied on private generators for the remaining 10 hours, resulting in a supply share of about 58% grid and 42% generators (see Section 2.3.1).

The use of electricity varies by end-use in the typical household. Almost all households (99.2%) have access to a source of energy for cooking, with gas being the primary source accounting for 96%, while only 11% relies on wood for cooking. However, for heating,

35 Hussein El Samra et al., Lebanese Solar Water Heater Market Study Report: 2017–2020 Update (Lebanese Center for Energy Conservation (LCEC), 2022).

36 Irène Beucler et al., Availability, Efficiency & Use of Home Appliances in Lebanon (Lebanese Center for Energy Conservation (LCEC), 2020).

37 Ahmad Houri, Biomass: A Diversity of Solutions, Issue Number 5, Cedro Exchange (United Nations Development Programme (UNDP) / CEDRO Project, 2013).

38 United Nations High Commissioner for Refugees (UNHCR) et al., VASyR 2023 – Vulnerability Assessment of Syrian Refugees in Lebanon: Thematic Energy Report.

Residential Energy Use Patterns

30% of households reported having no source of heating, while the rest rely on wood as the most commonly used heating source (41% in 2023), followed by diesel (22% in 2022 and 13% in 2023).[38]

Official reports and sources state that the highest electricity demand is the cooling and dehumidification sector in the residential sector, followed by lighting, domestic hot water and finally space heating. The share of space heating remains low because it is not included in the electricity use since the majority use wood or diesel to heat their households rather than electric systems.[39] In contrast, in the European Union the order is reversed: space heating has the highest electricity demand, followed by DHW, while cooling takes up only a minor fraction (Figure 2.3.2.2).[40], [41]

According to the climate zone's heating degree days (HDD) and cooling degree days (CDD), it is evident that we should primarily focus on the heating demand rather than the cooling demands. Based on this, we estimate that the heating will be provided by a traditional wood-fueled Sobia stove. Domestic hot water (DWH), lighting, and appliances will be powered by electricity, sourced from both a private generator and the public grid, while gas will be used for cooking. As for cooling, we will rely on passive strategies such as natural ventilation and the building's thermal mass and monitor the thermal comfort particularly in periods of heat stress.

39 Dr. Sorina Mortada (Lead Author) et al., The First Energy Indicators: Report of the Republic of Lebanon. figure 37 & section 4.2

40 Eurostat, Energy Consumption in Households - Statistics Explained.

41 Dr. Sorina Mortada (Lead Author) et al., The First Energy Indicators: Report of the Republic of Lebanon.

Table 2.3.2.1 - Residential Energy Sources in Lebanon according to the Bioclimatic Zones *(Continued on next page)*

Source: Author's elaboration based on Houri (2013), Beucler et al. (2020)

Table 2.3.2.2 - Comparison of Residential Energy Sources and Uses: EU vs. Lebanon

Source: Author's elaboration based on Eurostat and Mortada et al. (2018)

EU	%	ENERGY SOURCE	LEBANON	%	ENERGY SOURCE
Space Heating	63.5%	Natural Gas, Renewables, Oil, District Heat	Space Heating	not quantified	Electric Heater, Diesel, Wood
DHW	14.9%	Mix Gas, Electricity, Renewables	Cooling	19%	Electricity
Lighting + Appliances	not quantified	Electricity	DHW	7-8%	Electricity
Cooking	not quantified	Gas + Electricity	Lighting	5%	Electricity
Cooling	0.6%	Electricity	Appliances	not quantified	Electricity
			Cooking	not quantified	Gas

Table 2.3.2.1
(Continued)

	USAGE %	TYPE	USAGE	LOCATION	WIDESPREAD USE	BIOCLIMATIC ZONE*	PROS	CONS
SOLAR	**9.5%**	**Solar Thermal**	Domestic Hot Water	-	- Still a **minority**, but growing (2-3% of households 2010, and then **10% in 2020**) - Now stagnated due to crisis	-		
		PV panels	Electricity generation	-	- Rare before the crisis then **10x increase** around 2022 - From 47 MWp in 2018 to **870 MWp in 2022**	*WIDESPREAD*		
BIOMASS	**25.2%**	**Olive husk** (jift) direct combustion or indirect (pyrolysis and gasification)	Heating (compressed into pellets or briquettes)	Popular in northern and central Lebanon	- In some coastal areas that still produce olive oil (mostly south of Lebanon)	*1-2*	- cost effective biomass fuel	
		Wood	Stoves, Fireplaces	Traditional (rural/mountain areas) older houses or chalets	- Mostly in mountainous areas where we have forests	*2-3*	- Sustainable if sourced responsibly	- Air quality - Sourcing
		Other agricultural residues (olive pomace, pruned wine shoots, fruit tree residues...)	Heating	-	- In mountainous forest dense area which also have agricultural activities	*2-3-4*		
		Animal manure	Fireplaces biogas production (small scale)	Rural and farming communities	- In areas that have a predominantly agricultural activities	*3-4*	- Can be used for cooking, heating, and electricity generation	- Small scale
NON RENEWABLES	**65.3%**	**Liquified Petroleum Gas (LPG)**	Cooking (stove)	-			- Not reliant on electricity - Cost effective	- Requires proper ventilation for safety - Supply dependancy - Price fluctuation
		Diesel Oil	Heaters	Rural (specially in mountains) and urban areas	- Rare in the plateau area (4) which has absent central gas network for diesel supply		- High heat output - Long burn time	- High cost fuel - Pollution - Supply dependancy
		Electricity	Radiators, fan heaters, split AC units (with heating mode)	Used in cities and apartments	- Electricity in the plateau area (4) insufficient to heat large houses			- Electricity supply issues (power cuts) - Backing up by private generator or solar
		Gas (Butane)	Heaters	Homes with no central heating			- Portable and affordable	- Requires proper ventilation for safety

2.3.3 EXISTING HEATING AND COOLING PRACTICES

In the 19th century, the majority of Lebanese houses relied on local stoves and fireplaces to heat the main living room of the house. Biomass – mainly wood, wood pellets or wood shavings – and agricultural residues such as olive husk, fruit tree residues and animal manure were commonly used as heating fuel.[42] These heating systems operated based on direct combustion and were typically installed in the central Liwan or reception room of the house, and even though nowadays only 70% of all residential buildings across the Lebanese territory have access to a heating source, they continue to use direct combustion to heat up the space. In traditional houses, traditional heating systems such as the Sobia stove remain a prevalent solution since the building is not fit to accommodate modern centralized heating systems or ducted heating systems.[43] In some cases, other less efficient systems such as the Kenoun - a portable brazier used for both cooking and heating - may be adopted and moved between rooms as needed.[44] The following active and passive heating and cooling methods found in Lebanese traditional houses are detailed in the following tables 2.3.3.1 and 2.3.3.2.

The rest of the house, such as circulation, storage and sometimes kitchen typically remained unheated, and the occupants adopted heavy clothing and thick bedding to warm up. They also relied on the heavy wooden doors to close off any unused spaces in order to preserve heat, and the thick walls' thermal mass that provided delayed heat retention, and finally the solar heat gains on the first floor to warm up during the day. [45]

Additionally, it is worth noting that new wood burning stoves have significantly improved in performance. According to EN 13240 standards, stoves must reach a minimum efficiency of ≥50% [46], with modern models now achieving an efficiency rate of 75-80%. [47]

Lebanon's prevailing hot and dry mediterranean climate (Csa) requires specific design strategies to ensure thermal comfort during summer. Typically, buildings in such climates are designed with small and limited facade openings, light-colored and reflective materials, high thermal mass, evaporative cooling and in some cases earth sheltering. However, in the case of Douma, where Mediterranean (Csa) classification is influenced by a hot, dry and mountainous microclimate, the effectiveness and priority of these strategies shift. The order of importance must be adapted to reflect this unique local context, therefore requiring a more tailored approach to passive design. Passive and active cooling methods are therefore found in table 2.3.3.2 and include key passive cooling strategies such as:

1- Sun Shading: Reduces direct solar gains through apertures with the use of shutters, overhangs, or vegetation.

2- Thermal Mass: The heat sink effect plays an important role in regulating indoor temperature and improving thermal comfort. It refers to a material or system that absorbs, stores and gradually dissipates heat, acting as a thermal buffer that reduces temperature fluctuations - particularly valuable in the hot and dry climates and in both winter and summer.

3- Natural Ventilation and Vegetation: This effect is most effective when combined with adequate ventilation, whether natural or mechanical, and supported by evaporative cooling strategies such as the presence of trees or nearby water sources like a fountain, which help to cool and humidify the air.

4- Night flush: Opening the windows during cooler nights to expel heat and cool the structure down.

5- Shutters and Wind Control: Closing openings during the day or blocking unwanted wind or dust.

6- Compact Massing: An important but least effective strategy which requires having few small openings in the facade, offering a low surface to volume ratio, and enclosing most of the space with the least exposed surface area to the exterior. This helps in reducing heat transfers and therefore keeps a regulated balanced indoor thermal environment. The Lebanese house in Douma is an almost perfect cube, being the building shape the most compact and therefore suiting this strategy.

7- Reflective Materials: Using light colored plasters, materials, and roof finishes to minimize heat absorption.

8- Apertures and Glazing: Carefully positioned and shaded windows with appropriate glass type that filter light and heat gains.

42 Houri, Biomass: A Diversity of Solutions.

43 Amal Chkeir et al., "Assessment of Thermal Comfort in the Traditional and Contemporary Houses in Byblos: A Comparative Study," Energy and Built Environment 5, no. 6 (2024): 933–45, https://doi.org/10.1016/j.enbenv.2023.07.006.

44 A. Mosyak et al., "Thermodynamics of a Brazier Cooking System Modeled to Mimic the Lead Brazier of a Roman Ship," Journal of Archaeological Science: Reports 16 (December 2017): 19–26, https://doi.org/10.1016/j.jasrep.2017.09.005.

45 Jad Hammoud and Elise Abi Rached, "Evaluation of Thermal Comfort in the Traditional Bourgeoisie Houses in Beirut," International Journal of Applied Science 3, no. 1 (2020): 1–16, https://doi.org/10.30560/ijas.v3n1p1.

46 Nordisk Miljømærkning, Swan-Marked Closed Fireplaces (Svanemærkede Lukkede Ildsteder), Background document version 4.7 (Baggrundsdokument version 4.7) (Nordisk Miljømærkning, 2024).

47 Ole Jensen et al., Field Study of Energy Performance of Wood-Burning Stoves (2011), 1069, https://doi.org/10.3384/ecp110571062.

48 ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), ANSI/ASHRAE/IES Standard 90.2-2018: Energy-Efficient Design of Low-Rise Residential Buildings, ASHRAE, 2018. Table 5-1

49 ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), ANSI/ASHRAE/IES Standard 90.2-2018: Energy-Efficient Design of Low-Rise Residential Buildings. Table 5-2

50 U.S. Department of Energy, Guide to Home Heating and Cooling, DOE/EE-0338 (2010), https://www.energy.gov/sites/prod/files/2014/01/f6/homeHeating.pdf.

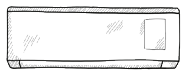
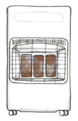
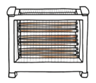
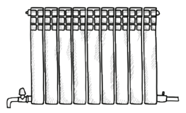
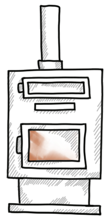
51 Ricardo L. Carvalho, "Energy Performance of Wood-Burning Stoves and Its Impact on Indoor Air Quality, Danish Building Research Institute" (Master's Thesis in Sustainable Energy Systems, University of Aveiro, Portugal, 2010).

52 ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), ANSI/ASHRAE/IES Standard 90.2-2018: Energy-Efficient Design of Low-Rise Residential Buildings.

Existing Heating and Cooling Practices

Table 2.3.3.1 - Common Active and Passive Heating Methods commonly found in Lebanon

Source: Author's elaboration based on [48-51]

STRATEGY	MECHANISM	SYSTEM	IMAGE	DESCRIPTION
ACTIVE	Convection (Conduction)	Heat pump		· No use for heating in winter · Radiators or Underfloor Heating (UFH) · Radiator less efficient (SCOP = 2.8 - 3.2) · UFH more efficient (SCOP = 3.5 - 4.5)
	Convection (Conduction)	AC Hot/Cold		· Very rare use for heating in winter · Can come in different type: window AC units (low), basic fixed speed split units (med), and inverter units (high) · All have different efficiencies
	Radiative Convection	Gas heater		
	Radiative Convection	Electric resistance heater (pluggable and moveable)		· Direct heating · Consumes a lot of electricity · Expensive · Depends on grid electricity (fossil fuels)
	Radiative Convection	Hydronic central heating radiator (water-based, wall mounted) - boiler running on electricity		· Best for homes with central heating · Saves energy compared to resistance heaters · Expensive to install · Depends on grid electricity (fossil fuels)
	Radiative (Convection)	Traditional lebanese stove "Sobia"		· Efficient for long heating periods (with high quality fuel) · Works well in cold areas (mountains) · Mazout (Diesel) is expensive and pollutes · Wood burning cause deforestation and indoor pollution · More efficient types of stove available on the market around 75-80 % efficiency [47]
	Radiative (Convection)			
	Radiative	"Kenoun" or portable brazier made of clay or metal (jift or charcoal)		· Low cost heating for small spaces, portable · Uses traditional fuels (jift), reducing waste · Very inefficient · Major health risks (Indoor Air Pollution) · Not efficient for large spaces and long term heating · Labor intensive (maintenance and refueling)
		Can also be fueled by "Narit" (jift and wood shavings)		
PASSIVE *most efficient*	Conductive Storage Radiative	Walls Thermal Mass		· Use of high thermal mass materials like sandstone (exterior) · Absorbs and retain (conduction) heat then releases it (direct radiation) · Natural convection around thermal mass
	Radiative	**Solar Orientation & Apertures**		· Maximize winter sun exposure · Potential Winter solar gains (Triple Arch)
	Radiative Conductive	Absorptive & Dark Colored Materials		· Low reflectivity (albedo) means more solar heat is absorbed · Heat gains in winter
least efficient	Conductive Convective	Compact Massing		· Limited openings to reduce heat loss (limits conduction) · Limited airflow in winter (trap warm air, reducing convective heat loss)

SYSTEM	IMPLEMENTATION ON HOUSE	BIOCLIMATIC ZONE	COP	NET EFFI-CIENCY	ENERGY SOURCE	PRIMARY SOURCE	FUEL FACTOR (PEF)	COST EFFICIENCY
Heat pump		-	3.8 [48]	1.95 (air to air / air to water)	**Electricity** (from grid)	Oil, hydro, solar	1.97	Expensive upfront, cheap to run if efficient [50]
AC Hot/Cold		-	2.2 (low) 2.9 (med) 3.8 (high) [48]		**Electricity** (from grid)	Oil, hydro, solar	1.97	Expensive upfront, cheap to run if efficient [50]
Gas heater		1		0.95 [49]	**Liquified Petroleum Gas**	Butane	1.10	
Electric resistance heater		1 - 4	1.00 (electrical)		**Electricity** (from grid)	Oil, hydro, solar	1.97	Expensive to run
Hydronic central heating radiator		2-3 (rare)	1.00 (electrical) [49] 0.90 (fossil fuel)		**Electricity** (for central boiler system)	Oil, hydro, solar	1.97	Expensive to install but cost-effective for central heating
Sobia (Diesel)		2 - 3 - 4		0.54 [51]	**Diesel** (used to be more common)	Diesel	1.10	Cheap fuel but inefficient
Sobia (Wood)		2 - 3 - 4			**Wood** (now more common after crisis) (most of the time wood is illegally cut)	Biomass (wood)	1.00	
Kenoun		1 - 4		0.10 - 0.20 [51]	**Charcoal** (fast burning) Olive oil residue "**Jift**" (slow burning)	Biomass / Charcoal	1.00	Cheap but inefficient
Narit		2 (rare) - 4		0.15 [51]	Olive oil residue "**Jift**" (slow burning) **Wood shavings**	Biomass		
Walls Thermal Mass	· Double pane Low- E on West, North, East · Clear glazing on South · **Prioritizing good solar access** · Organize floor plan to get winter sun penetration into daytime used spaces · Locate storage areas towards coldest wind (insulation) · Sunny wind protected outdoor spaces							
Solar Orientation & Apertures								
Absorptive & Dark Colored Materials								
Compact Massing								

Table 2.3.3.2 - Common Active and Passive Cooling Methods commonly found in Lebanon

Source: Author's elaboration based on [52]

STRATEGY	MECHANISM	SYSTEM	IMAGE	DESCRIPTION	IMPLEMENTATION ON HOUSE	BIOCLIMATIC ZONE	COP	ENERGY SOURCE	PRIMARY SOURCE	FUEL FACTOR	COST EFFICIENCY
ACTIVE	Convection (Conduction)	Heat pump		· Rarely used in Lebanon		1	3.81 [52]	Electricity (from grid)	Oil, hydro, solar	1.97	Expensive upfront, cheap to run if efficient
	Convection (Conduction)	AC Hot/Cold (direct expansion AC)		· Works well in moderate climates (Coastal and low altitudes) · Heat pump mechanism = efficient · Not ideal for cold mountain area · Depends on electricity availability		1 - 4	3.81 [52]	Electricity (from grid)	Oil, hydro, solar	1.97	Expensive upfront, cheap to run if efficient
most efficient	Radiative	**Sun Shading Devices**		· Prevents solar gains and blocks radiation · Minimize summer heat	· Use the shutters and block solar gains from the exterior · Thicken 1st floor wall as sun shading (like GF)						
	Conductive Storage Radiative	Thermal Mass		· Absorbs heat (day) and releases it when cooler (night)	· High thermal mass · Night flush is <u>necessary</u>						
	Convective	**Natural Ventilation**		· Oculus opening on top of the wall as exit point, and doors as entry point and Triple Arch big openings · Moves warm air out, brings cool air in (wind driven) · Enhances airflow through building	· Ventilate at night (nigh flush) to complement thermal buffering)						
PASSIVE	Convective Radiative Evaporative	**Vegetation & Shaded Outdoor Spaces**		· Provides shade (radiative) + moisture (evaporative) · In the case of an air movement, accelerates the local airflow, enhancing natural ventilation and cooling down the breeze	· Shade reduces solar heat gains · Adds moisture to the air so less effective than normal						
	Radiative Conductive	Reflective & Light Colored Materials		· High reflectivity (albedo) means less solar heat is absorbed · Can be ineffective in winter	· Reflective surfaces (light colors) · Reduces absorbed solar radiation						
	Conductive	Compact Massing		· Reduces heat gain by minimizing exposed exterior area							
	Evaporative	**Fountain and Water Points with Natural Ventilation**		· Cools air by evaporation	· *Not effective because of high humidity in the area*						
least efficient	Radiative	**Solar Orientation & Apertures**		· Glazing type according to the orientation	· Double pane Low- E on **West, North, East** · Clear glazing on **South + shading)**						

2.3.4 EMISSION FACTORS AND ELECTRICITY TARIFFS

This section assesses the environmental impact of residential electricity use in Lebanon expressed in carbon emission factors (EF) of both the public grid and the private generators, as well as the economic weight posed by electricity pricing under both systems (Figure 2.3.4.1).

Since there is no official published carbon emission factor for the Lebanese electricity grid, we derive an approximate value using the data provided by the International Energy Agency for the year 2022, specifically for the residential sector.

Public Grid EF (2022): [53]

CO_2 Emissions
= 0.4230 Mt CO_2
= 423,000,000 kg CO_2

Final Consumption of Electricity
= 5,367 TJ
= 1,490,833,333 kWh

Emission Factor EF (kg CO_2 / kWh)

$$= \frac{CO_2\ Emissions}{Electricity\ Consumption}$$

$$= \frac{423{,}000{,}000}{1{,}490{,}833{,}333}$$

EF GRID (kgCO_2/kWh) = 0.28

Private Diesel Generators EF: [56]

As mentioned earlier (Section 2.3.1) the typical generator efficiency is 25-30%. Therefore, we will select an efficiency (Eff) of 30% (0.3).

As for the EF diesel fuel, the IPCC indicates that:

$$EF_{DIESEL} = 74\,100 \text{ kg } CO_2/TJ = 74.1 \text{ kg } CO_2/GJ$$

Since 1 GJ = 277.78 kWh we calculate:

$$EF_{DIESEL} = \frac{74.1 \text{ kg } CO_2/GJ}{277.78 \text{ kWh/GJ}} = 0.27 \text{ kg } CO_2/kWh$$

$$EF_{GENERATOR} = \frac{EF_{DIESEL}}{Eff_{GENERATOR}}$$

$$EF_{GENERATOR} = \frac{0.27}{0.30}$$

EF GENERATOR = 0.90 kg CO_2/kWh

In order to determine the EF of the electricity used by the residential sector, we know according to the section of Domestic Energy Consumption that it is 58% from the public grid and 42% from the private diesel generators (Section 2.3.1). [55]

EF GRID + GENERATOR
= (0.28 x 0.58) + (0.9 x 0.42)

EF GRID + GENERATOR
= 0.54 kg CO_2/kWh

53 International Energy Agency (IEA), "Lebanon - Electricity."

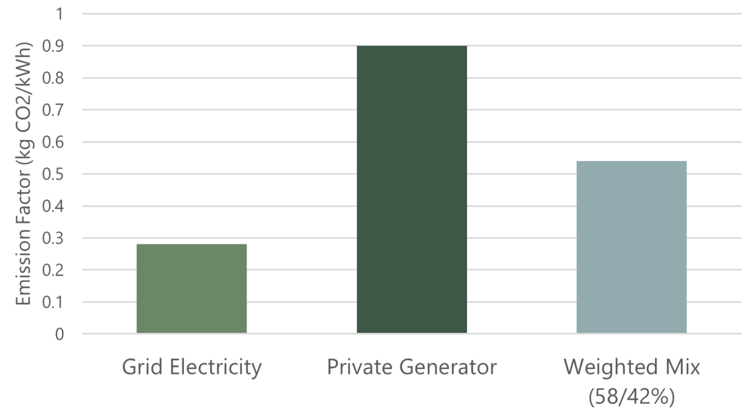
54 Darío R. Gómez and John D. Watterson, 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 2: Energy., Chapter 2: Stationary Combustion (Intergovernmental Panel on Climate Change (IPCC), 2006), Table 2.2.

55 United Nations High Commissioner for Refugees (UNHCR) et al., VASyR 2023 – Vulnerability Assessment of Syrian Refugees in Lebanon: Thematic Energy Report.

56 "Under Pressure, EDL Lowers Some of Its Tariffs," L'Orient Today, June 9, 2023, https://today.lorientlejour.com/article/1340039/under-pressure-edl-lowers-some-of-its-tariffs.html.

Figure 2.3.4.1 - Comparision of Emission Factors per Energy Sources in Lebanon (Environmental Impact)

Source: Author's elaboration



Electricity Tariffs:

In Lebanon, both the United States Dollar (USD) and the Lebanese Pound (L.L.) are used in parallel for transactions. As a result of the economic collapse in 2020, the exchange rate stabilized at approximately 1 USD = 89 000 L.L. by mid-2023. Electricity bills issued by the national utility Électricité du Liban (EDL) are settled in Lebanese pounds, even though the official pricing is referenced in US dollars.

As of June 2023, the EDL tariff was reduced from 0.27$/kWh to 0.26$/kWh, showcasing a slight adjustment in response to the inflation and energy supply [4]. A tiered pricing is set for $0.10/kWh for residential consumption up to 100 kWh/month, and $0.26/kWh for consumption above this threshold. In addition, fixed monthly fees were decreased by 25% (subscription and maintenance) amounting to approximately $4.80/month (e.g., subscription fee for 15A = $1.80, for 10A = $3.15, for 5A = $1.60, with $3.00 for rehabilitation and stamp duties). [56]

Subscription Fee (15A) = 1.80$
Subscription Fee (10A) = 3.15$
Subscription Fee (5A) = 1.60$
Rehabilitation and Stamp Duties = 3.00$
Total = 4.80$/month

In contrast, private diesel generator tariffs vary by region and provider, and are consistently more expensive than the public grid. As of early 2025, the standard rate was $0.34/kWh, increasing by 10% in rural and mountainous regions above 700m of altitude thus elevating the average to $0.37/kWh. [57]

These rates exclude the fixed monthly fees, calculated based on ampere capacity, such as access to generator services, basic maintenance, distribution cost and the operator profit margin. For instance, a 10A connection has a fixed charge of $7.64 while the 5A connection fixed charge is $4.29, and each additional 5A increase above the initial capacity is charged at $3.34. In the specific

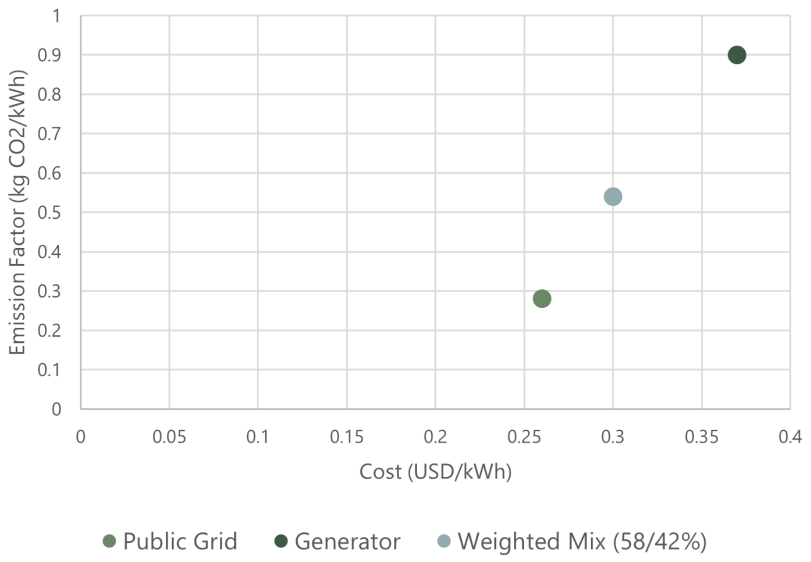


Figure 2.3.4.2 - Carbon vs Cost Tradeoff

Source: Author's elaboration

case of a residential household in Douma, located at an altitude of 1070 meters, the applicable electricity cost would amount to the $4.29 fixed fee (for the 5A connection) in addition to the generator consumption cost of $0.37/kWh, as the region qualifies as a mountainous zone (above 700m elevation).

To estimate the average monthly electricity consumption per household, we refer to an annual consumption of 6907 kWh (based on 2005 data) that equals around 575 kWh/month per household.[58]

Based on the usage distribution seen in section 2.3.2 - 58% of electricity provided by EDL and 42% from private generators – monthly consumption breaks down to 333.5 kWh from the public grid and 241.5 kWh from diesel generators.
0.58 x 575 kWh= 333.5 kWh/month
0.42 x 575 kWh= 241.5 kWh/month

For the EDL portion (58%), the first 100 kWh are priced at $0.10/kWh ($10.00), and the remaining 233.5 kWh at $0.26/kWh ($60.71), making up a total of $70.71. Adding the fixed monthly fees of $4.80 for the 15A plan, the **EDL cost amounts to approximately $75.51 per month.**

For the generator portion, assuming a mountainous location and a 10A connection, the energy cost amounts to 241.5 kWh x $0.37 = $89.36, to which the $7.64 fixed for the connection is added, totaling **$97 per month.**

In sum, the total monthly household electricity cost – combining the public and private supply – is approximately **$172.51 per month,** or **$2070.12 annually.**

57 "Slight Increase in Generator Rates in January," L'Orient Today, January 30, 2025, https://today.lorientlejour.com/article/1445726/slight-increase-in-generator-rates-in-january.html.

58 Houri and Korfali, "Residential Energy Consumption Patterns."

Emission Factors and Electricity Tariffs

Figure 2.3.4.3 - Cost vs Energy Delivered by Residential Electricity Sources in Lebanon (Bubble Size = Emission Factor)

Source: Author's elaboration

This significant economic burden related to the energy supply highlights the need for more affordable and reliable electricity provision, as well as sustainable.

The relationship between energy supply, monthly cost, and emission intensity is illustrated in Figure 2.3.4.3, which shows the combined weighted mix of energy that is common in households, as well as the inefficiency of private generators.

03 RESEARCH FRAMEWORK

3.1 PROBLEM STATEMENT

Non refurbishing traditional Lebanese houses, while culturally significant, often fail to meet modern thermal comfort standards, experiencing excessive heat in summer and inadequate warmth in winter due to limited passive climate responsiveness.

Current refurbishment methods do not always adequately address these thermal inefficiencies. Many interventions prioritize aesthetic or structural preservation without fully integrating climate-adaptive strategies.

> **How can traditional Lebanese houses be retrofitted to improve thermal comfort, minimize energy consumption, while preserving their architectural and cultural integrity?**

3.2 HYPOTHESIS & OBJECTIVES

The integration of passive, climate-responsive refurbishment strategies into traditional Lebanese houses can significantly enhance thermal comfort and reduce energy consumption, without compromising the architectural and cultural integrity of the buildings.

The primary objectives of this research are to:

1. Identify and analyze the thermal inefficiencies of the traditional Lebanese house types in a specified climate zone.
2. Investigate the existing passive design strategies of a typical house and their efficiency.
3. Evaluate existing refurbishment methods in terms of their climatic performance in both comfort and energy.
4. Propose climate-adaptive refurbishment guidelines that achieve a balance between energy performance and architectural preservation.

3.3 METHODOLOGY

This research is grounded in an interdisciplinary review of both empirical surveys, academic literature, technical reports, and national and international policy frameworks. The literature's aim was to establish a comprehensive understanding of architectural, thermal, and regulatory context in which traditional Lebanese houses operate, particularly with the current energy and comfort challenges.

The literature review focused on four main areas; first, the traditional house typologies and their historical development, where books such as *Architecture in Lebanon* by Friedrich Ragette [59] and *L'Habitation au Liban* by Jacques Liger-Belair [60] were informative sources on the context of regional spread, materiality, and passive strategies inherent to the architecture.

Second, in order to understand the thermal and energy performance, as well as the thresholds and retrofit potential of the house, technical standards and frameworks were consulted, including ASHRAE standards (55 [61], handbook 2021 [62], 90.2 [63], 169 [64]), and the *Thermal Standards for Building in Lebanon* (TSBL)[65].

Scientific studies and simulations addressing thermal comfort in vernacular Lebanese houses were used to establish baseline assumptions for heating, cooling, and daylight performance. [66] [67].

Thirdly, multiple reports from the International Energy Agency (IEA), the Lebanese Center for Energy Conservation (LCEC) and Eurostat were used to quantify residential energy consumption trends, heating fuel choices, emission factors and the structure of Lebanon's unreliable public grid, and articles such as *Residential Energy Consumption Patterns: The Case of Lebanon* [68] provided insight on household energy use.

Fourth and finally, the research incorporated international and regional manuals and guidelines on retrofitting old masonry structures deemed as heritage buildings, including CIBSE's TM39 *Energy Use in Buildings: Energy Benchmarking*[69], Historic England's restoration techniques and insight on insulation recommendations. [70] [71] [72] Technical datasheets on natural insulation materials chosen as part of the retrofit solution were consulted to assess material compatibility in conservation-sensitive contexts and performance on the energy and thermal comfort. Additional insights were taken from EU initiatives like *REFOMO* and *CORPUS – Euromed Heritage* on energy upgrades in traditional Mediterranean buildings[73]. Both the third and fourth sections were completed with the help of an empirical survey conducted that gave key insights into heating and cooling retrofitting strategies, thermal comfort, and spatial use of the house.

In parallel, a policy review examined the Lebanese Antiquities Law [74] and its impact on Lebanon's classified heritage and traditional Lebanese houses' future, the role of the Order of Engineers and Architects' TSBL and LIBNOR in outlining minimum thermal performance values for buildings.[75]

Together, this mixed-methods approach – combining both quantitative and qualitative data - shaped the foundation for the empirical, analytical, and simulation-based phases of this research. They provided a layered understanding of historical, technical, and lived-experience perspectives, while revealing critical gaps in policy enforcement, user awareness and the practical implementation of retrofit strategies in traditional Lebanese buildings.

To evaluate the thermal performance of traditional Lebanese houses and the effectiveness of retrofit strategies, a sequential simulation approach was adopted, starting from a baseline passive condition to complex intervention scenarios.

The process began with Case A (Adaptive), which represents the pre-intervention state of the building. In this model, the house was simulated as a passive structure without internal loads or active systems, allowing for an assessment of thermal discomfort based solely on the materiality and geometry of the original envelope in response to external environmental conditions.

The second stage introduced Case N (Norm), in which the same house was modeled with the addition of a basic heating system and typical internal loads, including residential occupancy, lighting, and equipment. This scenario allowed for the calculation of discomfort percentages and a comparative analysis with Case A, offering insights into how much comfort improvement could be attributed to the presence of internal heat gains and active heating.

Subsequently, Case S (Standard) was developed in alignment with the national building envelope standards outlined in the Thermal Standards for Buildings in Lebanon (TSBL). This model applied improved thermal insulation values to the envelope while maintaining the same internal loads and heating system as Case N. By comparing thermal comfort levels across Cases A, N, and S, as well as energy demand between Cases N and S, the analysis quantified the impact of envelope upgrades on both comfort and energy performance.

Finally, a series of Case O (Optimized) models were simulated to test the effects of specific passive and active

59 Ragette, Architecture in Lebanon: The Lebanese House during the Eighteenth and Nineteenth Centuries.

60 Jacques Liger-Belair, L'habitation au Liban: The dwelling in Lebanon, Éd. rev. et augm (Geuthner, 2000).

61 ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), ANSI/ASHRAE Addendum d to ANSI/ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy, Addendum D, ANSI/ASHRAE Standard 55-2017 (ASHRAE, 2020), https://www.ashrae.org/standards-addenda.

62 ASHRAE, ASHRAE Handbook - Fundamentals, 2021st ed. (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2021), 55.

63 ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), ANSI/ASHRAE/IES Standard 90.2-2018: Energy-Efficient Design of Low-Rise Residential Buildings.

64 ASHRAE, NSI/ASHRAE Addendum a to ANSI/ASHRAE Standard 169-2020: Climatic Data for Building Design, Addendum A, ASHRAE, 2021.

65 Order of Engineers and Architects of Beirut; LIBNOR; ECOTECH Engineering; ADEME; ALMEE; ASHRAE Lebanese Chapter; LGBC, Thermal Standard for Buildings in Lebanon (TSBL).

66 Chkeir et al., "Assessment of Thermal Comfort in the Traditional and Contemporary Houses in Byblos."

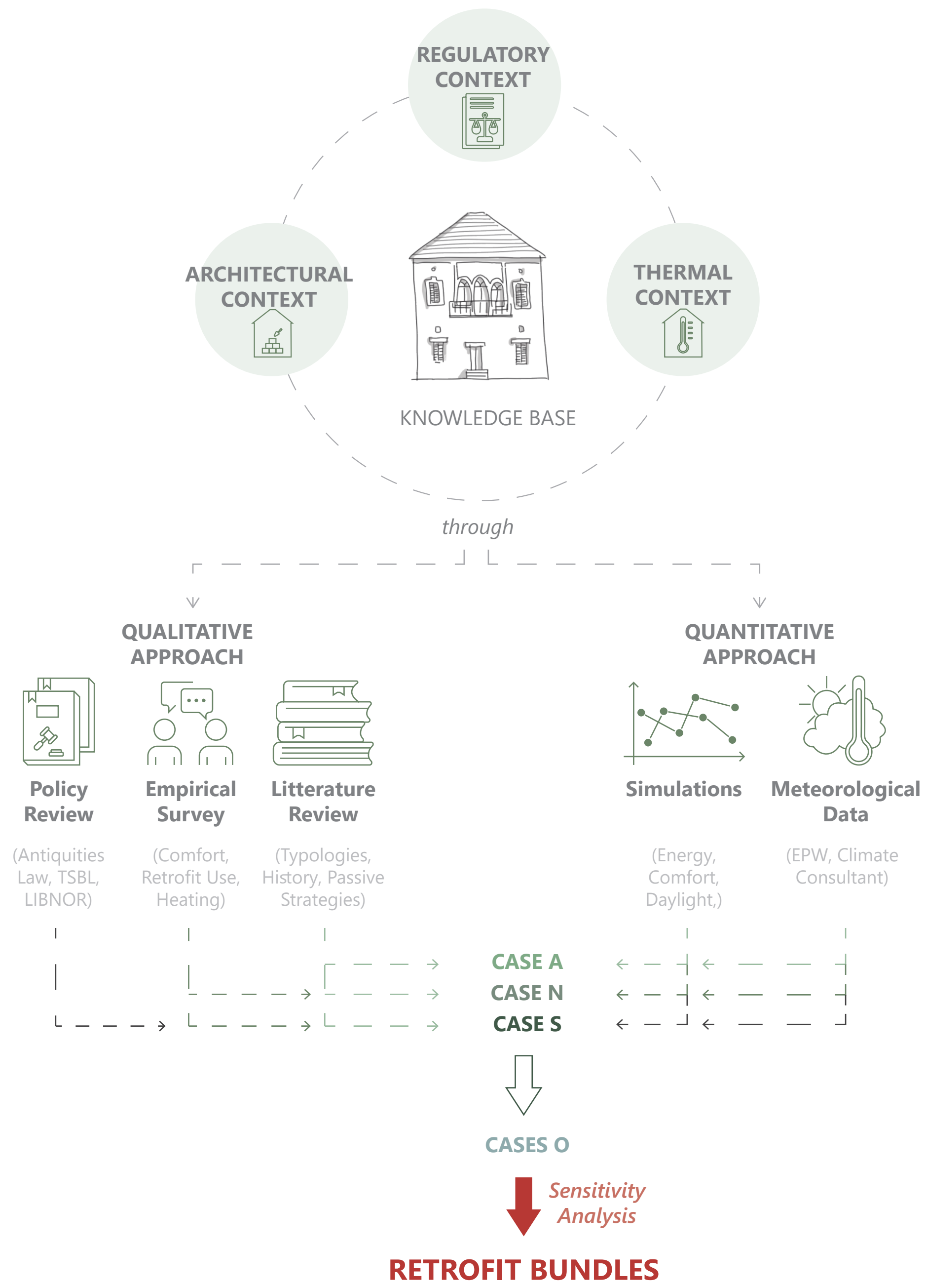
67 Jad Hammoud and Elise Abi Rached, "Evaluation of Thermal Comfort in the Traditional Bourgeoisie Houses in Beirut."

68 Houri and Korfali, "Residential Energy Consumption Patterns."

69 Chartered Institution of Building Services Engineers, TM39: Energy Use in Buildings: Energy Benchmarking (CIBSE, 2009), https://www.cibse.org/knowledge-research/knowledge-portal/tm39-building-energy-metering.

70 Historic England, Energy Efficiency and Historic Buildings: Insulating Solid Ground Floors (Historic England, 2012), https://historicengland.org.uk/images-books/publications/eehb-insulating-solid-ground-floors/.

retrofit strategies. A sensitivity analysis was conducted to isolate and evaluate the influence of individual interventions—such as roof insulation, improved glazing, thermal mass, shading, and HVAC upgrades—on both discomfort reduction and energy savings. This final step enabled the identification of the most effective measures, with a methodological emphasis on prioritizing passive solutions before integrating active systems as necessary to achieve target performance levels.



71 David Pickles, "Energy Efficiency and Historic Buildings: Insulating Solid Walls," Historic England, March 2012.

72 Nicholas Heath, Energy Heritage: A Guide to Improving Energy Efficiency in Traditional and Historic Buildings. (Changeworks, 2008).

73 European Union (MEDA Programme) and Antoine Fischfisch, Douma – CORPUS – Euromed Heritage.

74 Nalbandian, "LibGuides."

75 Order of Engineers and Architects of Beirut; LIBNOR; ECOTECH Engineering; ADEME; ALMEE; ASHRAE Lebanese Chapter; LGBC, Thermal Standard for Buildings in Lebanon (TSBL).

3.3.1 CASE STUDY TYPOLOGY

(From Left to Right)

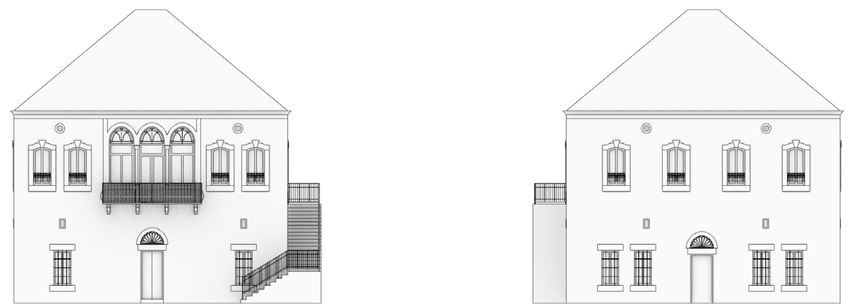


Figure 3.3.1.1 - Facades West, East

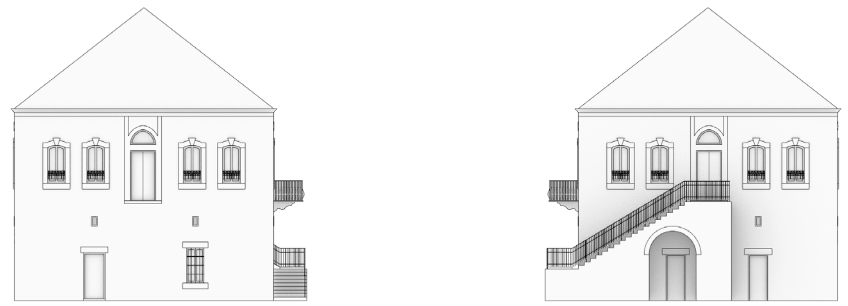


Figure 3.3.1.2 - Facades North, South

Source: Author's elaboration

The case study house is a typical central hall house with its characteristic triple arches on the west facade (facing the valley view), in the climatic zone of Medium Mountains, of the village of Douma (Section 2.1, Table 2.1.1).

The house was constructed in 1886 and is used as a basic model in this thesis although it is not known about its current state anymore.

The central hall house typology is also the most found typology on the Lebanese territory, especially in mid mountainous areas. It depicts the most authentic Lebanese architecture according to Friedrich Ragette who calls it the "Lebanese house par excellence" and is the most widespread type of house in the country despite its appearance at a later date than the other typologies.[76] Even though the central hall house comes with multiple different potential combinations, the houses were usually built by simply following traditions, with no plans or documents. This gave birth to a standard of building that is almost similar in every house, from the wall thickness and materials to the triple arch orientation which is also dictated by the mountainous topography of Lebanon that gives it a majoritarian westward orientation. The choice of this house was simply made because of its most typical plan distribution, orientation, and most typical dimensions, characteristics that are mostly found in all houses of the same typology. Moreover, the case study will be discussed in more details in Chapter 4, Section 4.2.3.

76 Ragette, Architecture in Lebanon: The Lebanese House during the Eighteenth and Nineteenth Centuries.

3.3.2 CLIMATE TYPE AND WEATHER FILE PROCESSING

The majority of traditional Lebanese houses that are restored or intact are condensed in the mountainous regions, since the wars and other tragedies led to the gentrification of the coastal cities and their old centers, and also numerous coastal cities were not as developed as today, only counting a small number of Lebanese houses and all the rest are new buildings. For example, Jounieh, used to be for agriculture, had a few Lebanese houses and the souk, then people migrated from conflict zones in Lebanon to the outskirts of big cities such as Beirut and settled in Jounieh and other areas, majority of the buildings are new with some preserved and abandoned Lebanese houses.

Douma was selected due to its abundance of traditional Lebanese houses, many of which are preserved or restored. This gives the village its inherent and distinctive traditional character. Moreover, its climate of **medium altitude mountains** gives us the perfect opportunity to tackle both heating and cooling, acting as a middle option between coastal and plateau, and the high-altitude mountains.

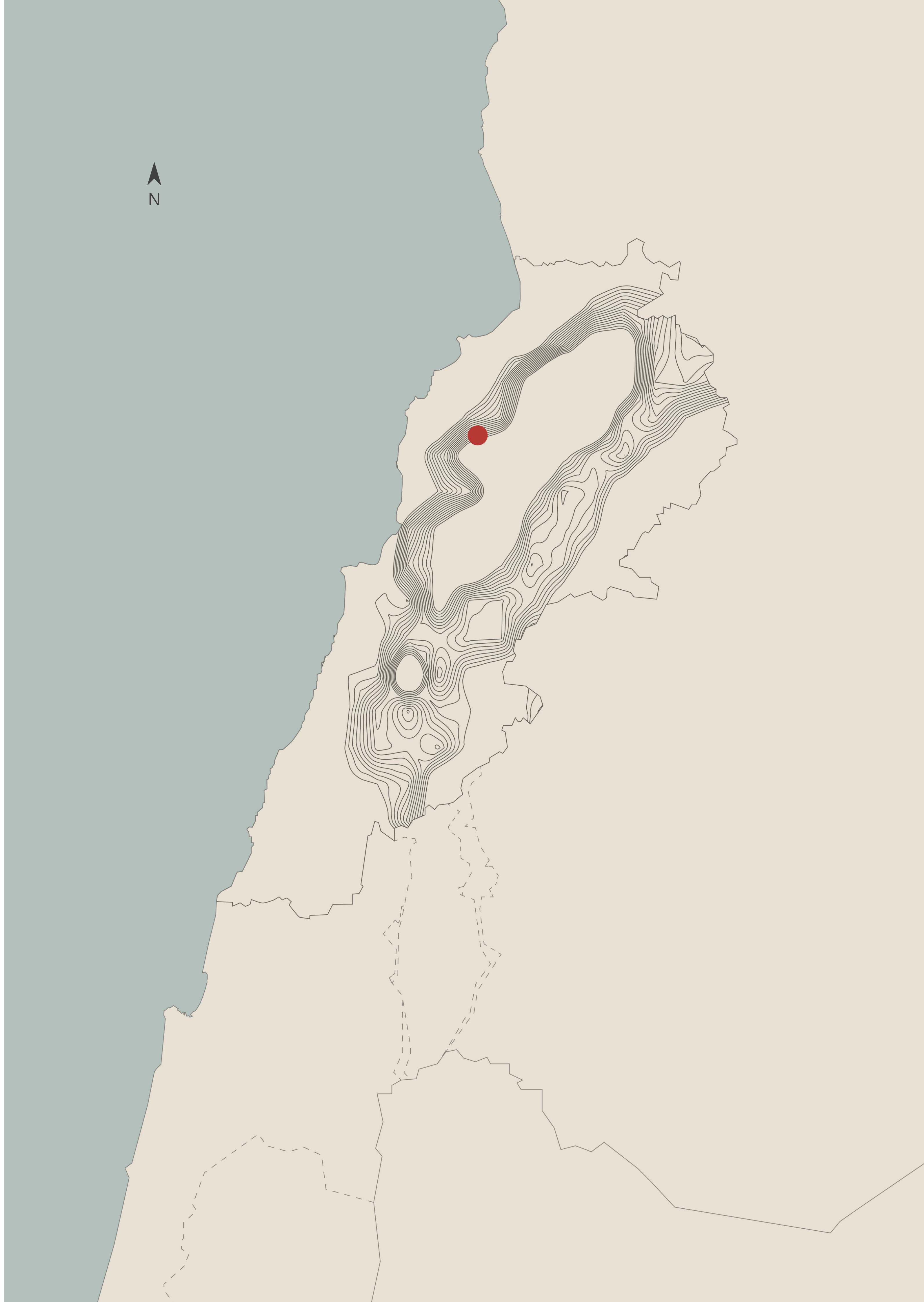
The EPW file is very important data that was used to conduct all the simulations. It is a formatted weather data that is used in energy and environmental simulations which contains information on temperature, humidity, wind speed and direction, solar radiation, precipitation, and other information that may be relevant to the simulating software. This file is based on a typical meteorological year or TMY which is basically typical weather conditions put together with data of different years for the location selected.

Since Douma or any other towns of the same climatic zone did not have an EPW file, I had to build my own using the EPW file of a nearby city which has similar altitude and weather patterns. The city of **Ifrane, Morocco** was chosen because of the similar yearly temperatures, solar radiation availability, relative humidity and season patterns. Both have cold winters, reach moderate temperatures in the shoulder seasons, then have higher temperatures in the summer.

Douma however has a slightly warmer winter, and different coordinates. The data was processed in Ladybug on Rhino, cross referenced with multiple weather sources to determine the yearly temperature average, then modified the EPW file as well as the coordinates and the altitude (Douma is slightly more elevated than Ifrane).

Figure 3.3.2.1 - Mapping of EPW File Coverage across Medium Mountain and Plateau Climatic Zones

Source: Author's elaboration



3.3.3 EMPIRICAL SURVEY OF TRADITIONAL LEBANESE HOUSES

A survey was conducted to gain key insights into how traditional Lebanese houses have been adapted to meet modern comfort needs, and to identify the most common retrofit strategies adopted by homeowners. It provided valuable information on both the technical solutions and the challenges encountered, as well as on regional typical approaches to achieving thermal comfort and spatial comfort (Figure 3.3.3.1).

The survey specifically targeted everyday residents without professional knowledge in architecture or building renovations, in order to capture practical experience-based perspectives.

The results were used to complement the literature research as well as the practical research conducted through simulations. Complemented with the context of the house and the energy and comfort simulations we are able to parameterize the strategies and implement them on a broader scale. Then the impact of those strategies is understood through energy and comfort simulations.

A total of 29 survey respondents participated in the empirical data collection, each residing in a different traditional Lebanese house and located across various climatic zones in Lebanon. The survey was distributed online via a shared Google Forms link and collected using a snowball sampling method over a period of 3 days in June 2025. The survey did not restrict the answers to a specific season, allowing respondents to reflect on year-round comfort conditions and adaptation strategies. The results were compiled and analyzed using Microsoft Excel, where data was sorted and visualized to extract common patterns in occupant behavior, retrofitting interventions, spatial use of the house and heating and cooling methods across the diverse housing typologies and environmental and climatic context.

Some challenges related to the accuracy and completeness of the participants' responses were identified. Specifically, some participants demonstrated limited awareness of the physical implications or technical details of their retrofit interventions. For example, while respondents accurately indicated the type of heating system used (e.g., radiators), they often excluded related construction impacts (e.g., underfloor piping, tile removal and replacement). As a result, data interpretation required cautious cross-referencing between answers and, in some cases, assumptions were made based on typical construction practices to fill in missing or inconsistent details.

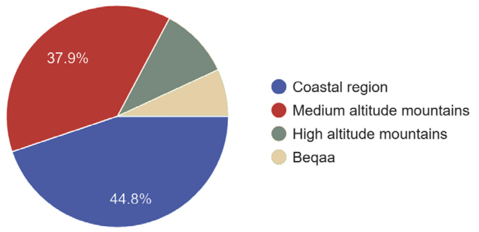
In order to ensure comparability with the climate zone of Douma, only survey responses from participants located within the same medium altitude mountain climatic zone were considered. After this post-processing step, the sample size was reduced to 12 participants (Figure 3.3.3.2).

Figure 3.4.4.1 - Survey results for entire Lebanese territory

1

Where is your house located?

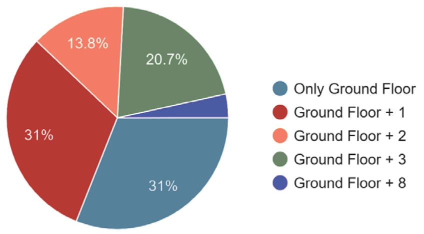
29 responses



2

Number of floors in your house:

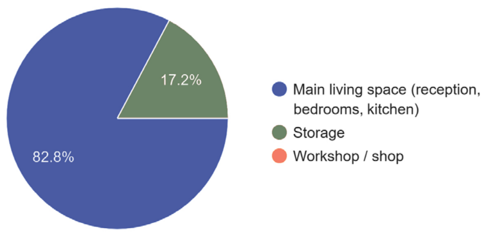
29 responses



3

What is the main use of the ground floor?

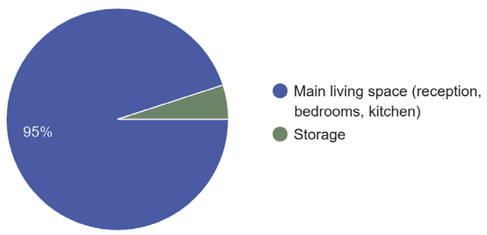
29 responses



4

What is the main use of the upper floor(s)?

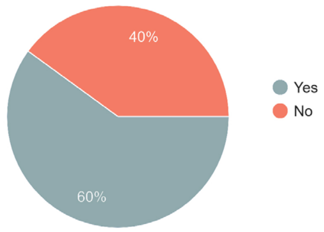
20 responses



5

Are the floors internally connected?

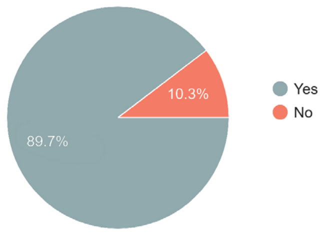
20 responses



6

Has your house been restored?

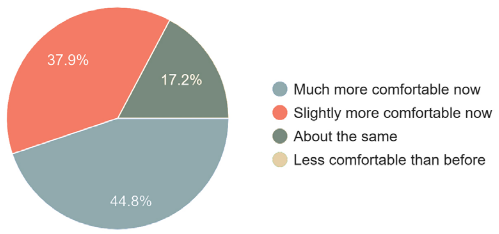
29 responses



7

How would you rate the current comfort compared to before restoration (if known)?

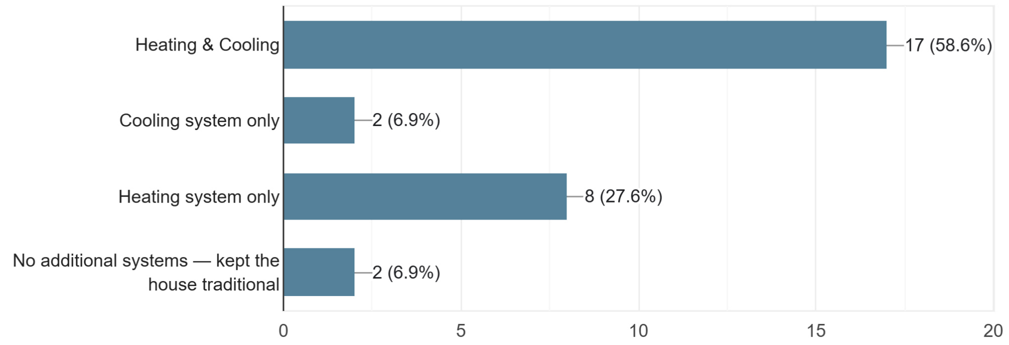
29 responses



8

Which of the following systems did you add during restoration? (check all that apply)

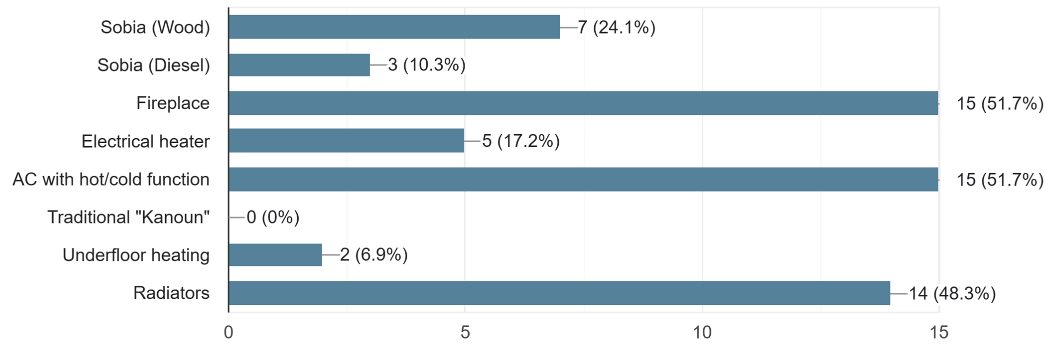
29 responses



9

What type of heating do you use? (check all that apply)

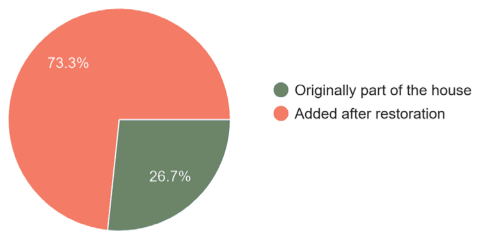
29 responses



10

Only if you have a fireplace, was it:

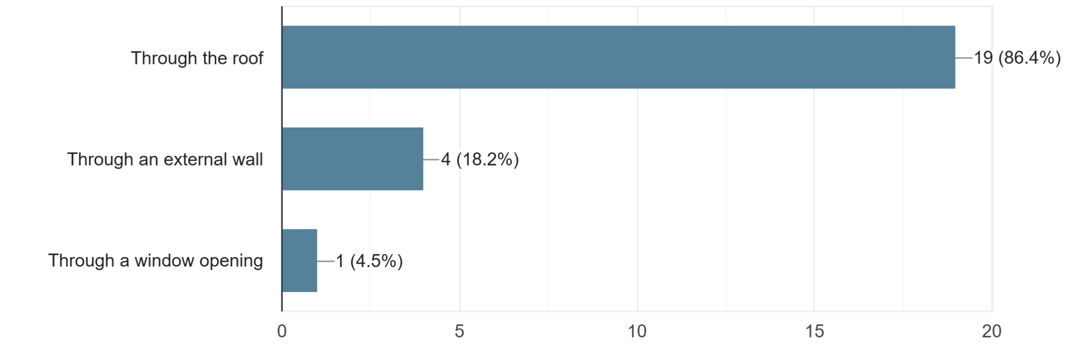
15 responses



11

In the case of a heating system that produces smoke (e.g. sobia, fireplace), where are the ducts/chimneys evacuating the smoke? (check all that apply)

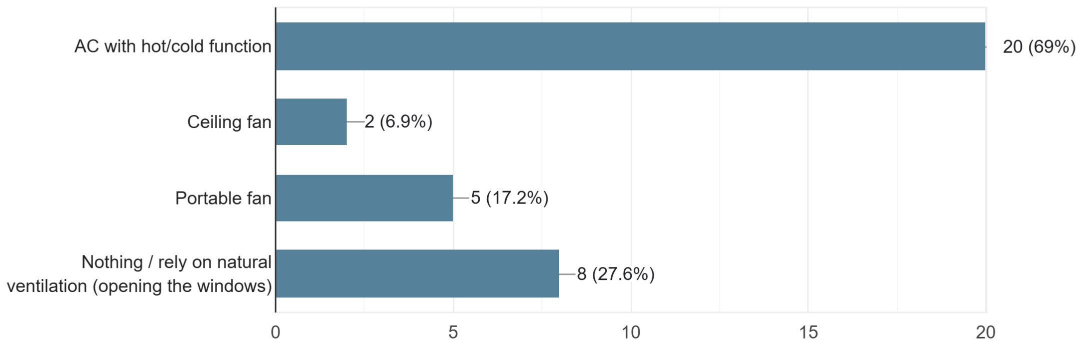
22 responses



12

What do you use for cooling in summer? (check all that apply)

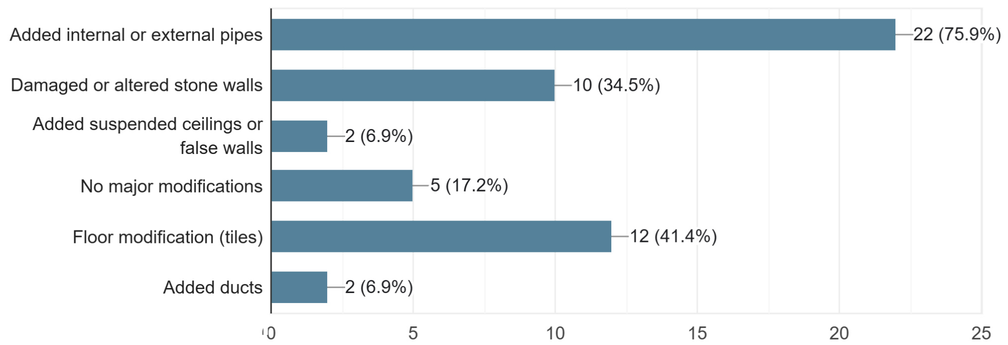
29 responses



13

Did the installation of heating or cooling systems (e.g. AC, radiators, underfloor heating) require any of the following modifications to the house? (check all that apply)

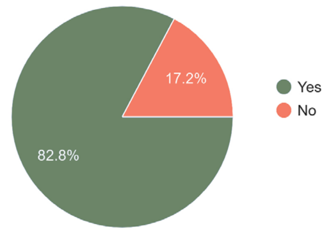
29 responses



14

In winter, do you heat the living room?

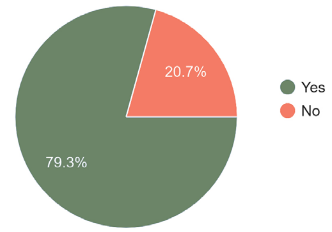
29 responses



16

Do you also heat the bedrooms?

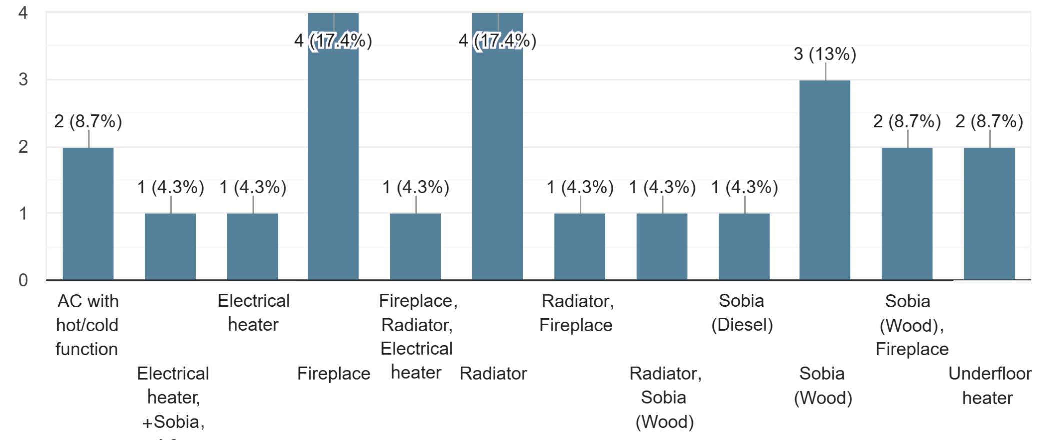
29 responses



15

If yes, with what?

23 responses



17

If yes, with what?

22 responses

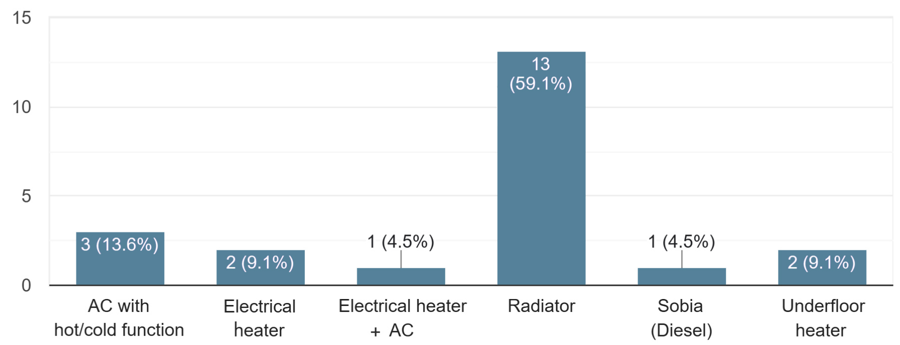
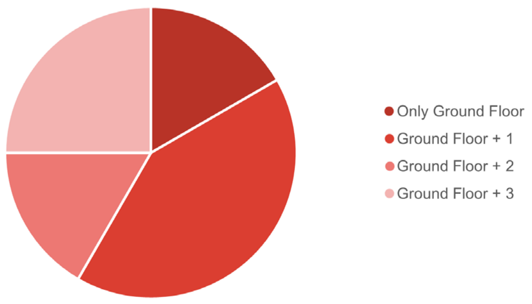


Figure 3.4.4.2 - Processed Survey Results for the Medium Altitude Mountains Climatic Zone

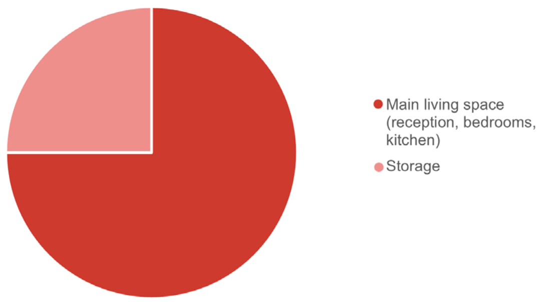
1

Number of floors in your house:



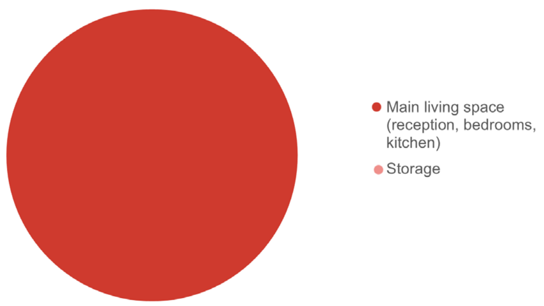
2

What is the main use of the ground floor?



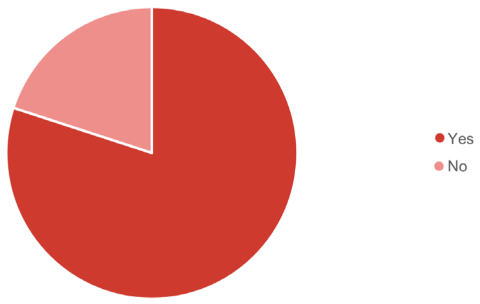
3

What is the main use of the upper floor(s)?



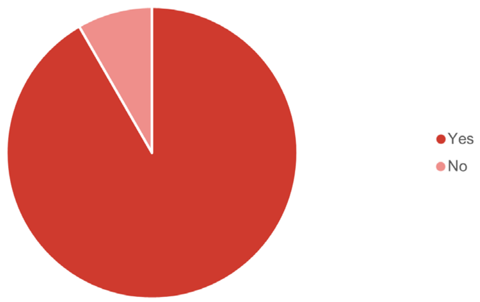
4

Are the floors internally connected?



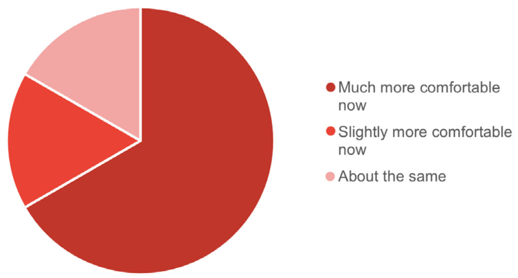
5

Has your house been restored?



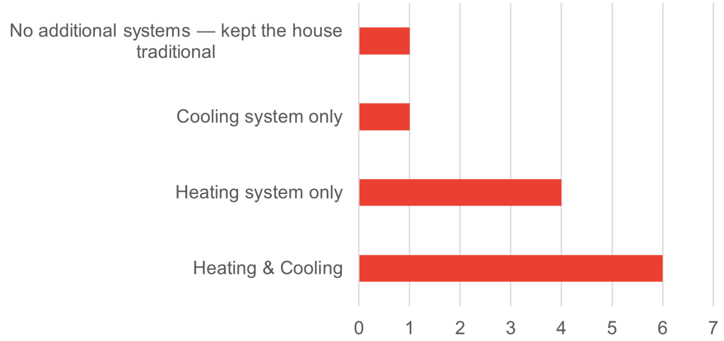
6

How would you rate the current comfort compared to before restoration (if known)?



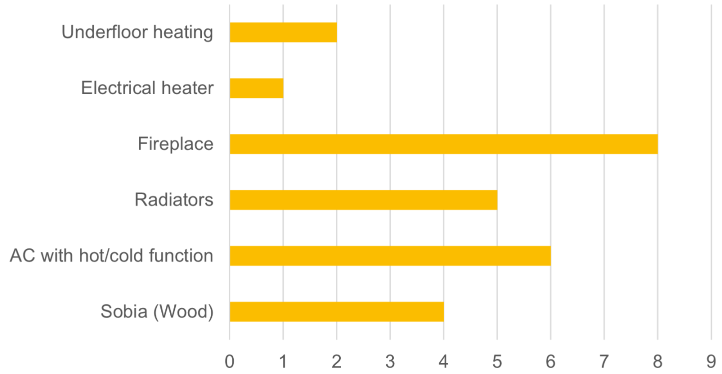
7

Which of the following systems did you add during restoration?



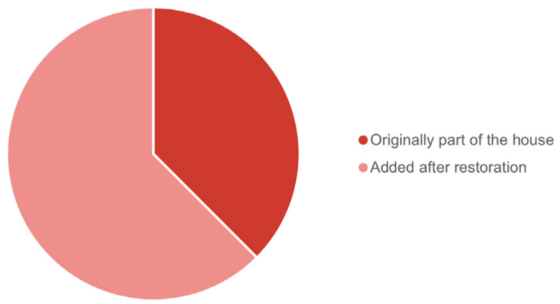
8

What type of heating do you use?



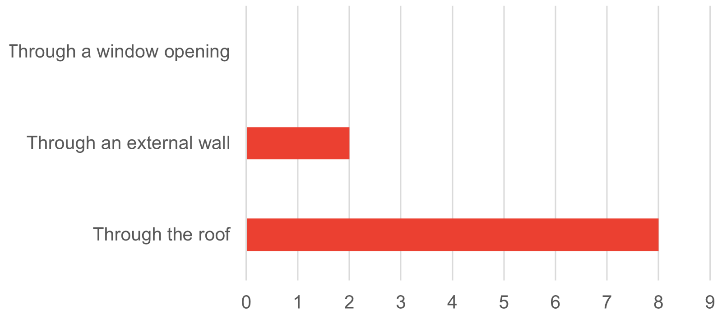
9

Only if you have a fireplace, was it:



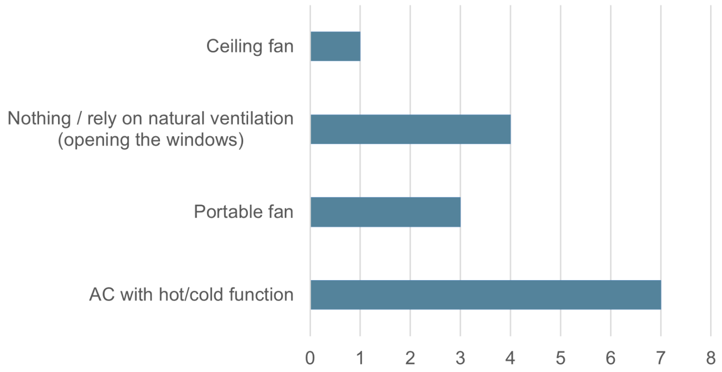
10

In the case of a heating system that produces smoke (e.g. sobia, fireplace), where are the ducts/chimneys evacuating the smoke?



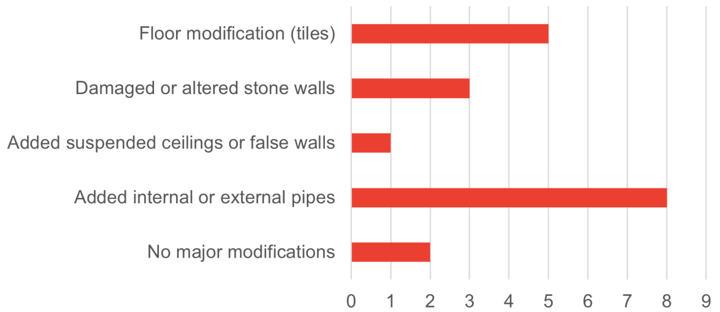
11

What do you use for cooling in summer?



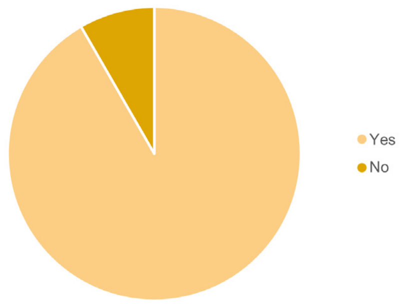
12

Did the installation of heating or cooling systems (e.g. AC, radiators, underfloor heating) require any of the following modifications to the house?



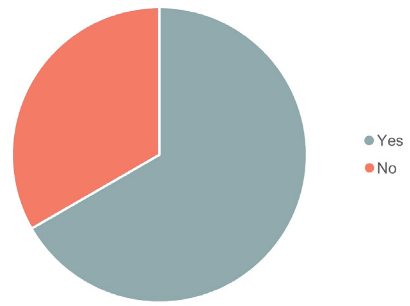
13

In winter, do you heat the living room?



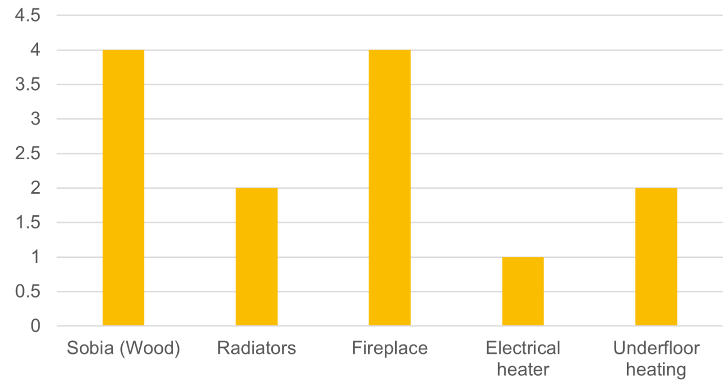
15

Do you also heat the bedrooms?



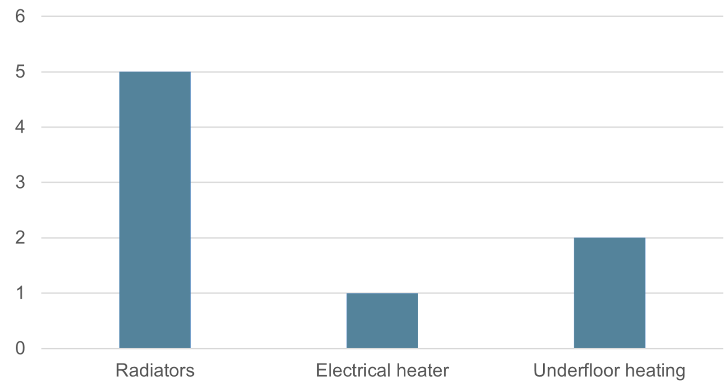
14

If yes, with what?



16

If yes, with what?



3.4 KEY PERFORMANCE INDICATORS (KPIS)

To evaluate the thermal performance and comfort of the traditional houses under different intervention strategies, a set of measurable Key Performance Indicators (KPIs) is established. The indicators are grounded in international standards, and provide a comprehensive framework to assess thermal comfort, daylight requirements, and building envelope performance. These KPIs allow for a consistent and comparative analysis of the Indoor Environmental Quality (IEQ), supporting informed decision-making rooted in factual assessment.

3.4.1 COMFORT THRESHOLDS

The following section details the comfort-based indicators used in this study, including a percentage of time within the comfort threshold, Predicted Mean Vote (PMV and Predicted Percentage of Dissatisfied (PPD) values with their respective ranges, temperature and humidity fluctuations, and finally comfortable indoor air velocity. We will use the ASHRAE 55 (Thermal Environmental Conditions for Human Occupancy), specifically Chapter 9 on thermal comfort to determine the threshold values.[77]

The ASHRAE Standard 55 defines thermal comfort as a condition in which at least 80% of occupants find the indoor environment thermally acceptable or neutral, meaning they feel neither too hot nor too cold. This comfort zone, also referenced in ISO 7730 [78], is illustrated in a psychometric chart that represents acceptable ranges of air temperature, relative humidity and mean radiant temperature serving as a reference to identify thermal comfort thresholds and occupant satisfaction. Maintaining conditions within this range supports both energy efficiency and indoor environmental quality (IEQ).

However, it is important to acknowledge that thermal comfort is not only framed by overall indoor conditions, but also by the presence or absence of thermal uniformity. Even when a person experiences a thermally neutral environment, localized discomfort – such as draft, cold windows, or hot surfaces – can lead to dissatisfaction. These fluctuations impose a great physiological effort of the body to maintain thermal equilibrium. ASHRAE 55 acknowledges that distinguishing between uniform and non-uniform thermal environments and therefore proposes different comfort thresholds. While a fully uniform environment can ensure acceptability for up to 90% of the occupants, the standard allows for a reduction to an acceptability of 80% in non-uniform environments.

77 ASHRAE, ASHRAE Handbook - Fundamentals. Chapter 9: thermal comfort

78 ISO 7730: Ergonomics of the Thermal Environment — Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, Standard ISO 7730:2005, International Organization for Standardization, 2005.

1 Adaptive Comfort Indicators

To quantify thermal comfort in naturally ventilated and seasonally heated buildings, the ASHRAE 55 introduces the adaptive comfort model, a model that relates indoor operative temperature to the prevailing mean outdoor temperature and defines acceptable comfort thresholds according to the outdoor conditions.

In this study, one indicator is reported, for a reason that will be detailed in a later chapter. The percentage of time above the upper threshold corresponds to the overheating hours, which should be minimized. The ASHRAE 55 requirement is met if **at least 80% of occupied hours fall within the adaptive band**, and for a stricter criterion the requirement is ≥ 90%.

2 Indoor Temperature and Humidity Fluctuations

Thermal comfort is also influenced by the variation in indoor air temperature and relative humidity (RH). ASHRAE 55 outlines seasonal comfort threshold as follows:

Summer conditions: **23°C – 26°C with 30-60% RH**
Winter conditions: **20°C – 24°C with 30-60% RH**

Maintaining a relative humidity within the 30-60% range is important for occupant health and comfort. High humidity levels (above 60%) can cause discomfort, encourage mold growth and potential indoor air quality issues, and increase cooling loads since moist air feels warmer, thus requiring air conditioning and dehumidification. Conversely, low humidity (below 30%) can lead to dry skin, throat and eyes irritation and increased respiratory discomfort.

The ASHRAE 55 recommends a seasonal humidity range of 30-40% in winter in order to prevent dryness, and on the other hand 50-60% in summer to prevent excess moisture buildup.

3 Air Velocity

Air velocity plays an important role in thermal perception, particularly in natural ventilated spaces. In warm environments, increased air movement can enhance cooling, whereas in cold environments, it is preferable to avoid it. According to the ASHRAE 55 (Thermal Environmental

Conditions for Human Occupancy), the acceptable range for indoor air velocity in typical occupied spaces lies between **0.25 to 0.5 m/s.** [79]

As seen in table 3.4.1.1, excessive air movements cause draft, while insufficient movement can lead to a sensation of stuffiness, especially in stagnant indoor environments. Assessing air movement can help in planning naturally ventilated strategies and selecting appropriate fan systems.

79 ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), ANSI/ASHRAE Addendum d to ANSI/ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy.

Air Velocity	*Probable Impact*
Up to 0.25 m/s	Unnoticed
0.25 to 0.5 m/s	Pleasant
0/5 to 1 m/s	Generally pleasant, but causes a constant awareness of air movement
1 to 1.5 m/s	From slightly drafty to annoyingly drafty
Above 1.5 m/s	Requires corrective measures if work and health are to be kept in high efficiency

Table 4.4.1.1 - Air Velocity Impact on Comfort

Source: Author's elaboration adapted from ASHRAE Standard 55 (Thermal Environmental Conditions for Human Occupancy) [79]

3.4.2 DAYLIGHT REQUIREMENTS

Daylight is an important component of indoor environmental quality. It's a factor that influences visual comfort, occupant well-being, and energy demand. Recognizing its importance, the European standard EN 17037 was introduced as the first technical norm specifically addressing daylight in buildings.

It establishes measurable criteria for the needs of natural light, taking into account the Average Global Horizontal Illuminance specific to the building's location in order to determine the acceptable thresholds. The standard also provides calculation methods that reflect the variability of daylight throughout the year.

These indicators provide the minimum requirements for two main aspects that will be included in the analysis: Daylight provision and protection from glare.

1- Daylight provision[80]

First of all, daylight provision is the quantity of natural light available in an indoor space that ensures sufficient illumination in order to carry visual tasks without relying on artificial lighting.

$$D_T = \frac{E_T}{E_{v,d,med}}$$

$$D_{TM} = \frac{E_{TM}}{E_{v,d,med}}$$

D_T, D_{TM} = Target and minimum target daylight factor

$E_{v,d,med}$ = median diffuse horizontal skylight illuminance

We calculate it by extracting Douma's average global horizontal illuminance using the EPW weather file:
Ev,d,med = 24,285 lux

Next, we calculate the average requirement for our space according to the standard EN 17037 for a fraction of daylight hours F = 50%.

ET = 500 lux
for F PLANE, % = 50% of the space

80 "EN 17037 Daylight Provision - ClimateStudio Latest Documentation," accessed May 10, 2025, https://climatestudiodocs.com/docs/daylightEN17037.html.

Level of recommendation for vertical and inclined daylight opening	*Target DF (lux)*	*Faction of space for target level F plane (%)*	*Minimum target DF (lux)*	*Faction of daylight hours F time (%)*
Minimum	1.23%	50	0.41%	95
Medium	**2.06%**	**50**	**1.23%**	**95**
High	3.09%	50	2.06%	95

Table 3.4.2.1 - Daylight Factor Thresholds for Douma, Lebanon

Source: Author's elaboration according to the EN 17037 standard

ETM = 300 lux
for F PLANE, % = 95% of the space

We then calculate our daylight factor threshold values, which gives us the target daylight factor that is tailored to our specific building's location (Table 3.4.2.1).

2- Protection from Glare

Glare is a visual disturbance, caused by overly bright areas or strong contrast between light and dark within the field of view. It can lead to discomfort or even reduced visual performance.

Typically, the use of shading devices or specific glazing characteristics helps in mitigating the risks and promoting a more comfortable space. [81]

81 Daylight in Buildings, EN 17037:2018+A1:2021, European Committee for Standardization (CEN), December 2021; "EN 17037 Daylight Provision - ClimateStudio Latest Documentation."

3.4.3 ENERGY PERFORMANCE AND CARBON FOOTPRINT

In parallel with comfort and daylight criteria, building performance is also assessed through energy efficiency and environmental impact. To complement thermal comfort evaluations, this section introduces key indicators rooted in the ASHRAE 90.2 and ASHRAE 189.1 standards, focusing on energy consumption, heating and cooling loads and carbon emissions. [82]

Following the ASHRAE 90.2 on Energy Performance Standards, the energy consumption known as the Annual Energy Use Intensity (EUI) is calculated per square meter of floor area. This metric provides a baseline for comparing energy demands across different retrofit scenarios.

$$EUI = \frac{\textit{Total Annual Energy Consumption}}{\textit{Total Floor Area } m^2}$$

Based on an average household Total Annual Energy Consumption of 6907 kWh[83] - equivalent to 1727 kWh per capita assuming an average household size of 3.8 occupants[84] - and a total floor area of 270 m²:

$$EUI = 6907 / 270\ m^2$$
$$EUI = 25.58\ kWh/m^2/year$$

Moreover, those annual energy demands are divided into multiple loads, including heating and cooling expressed in kWh/m2/year. We calculate them by dividing the annual heating or cooling energy consumption by the building floor area in m². This indicates the envelope's thermal performance and the effectiveness of passive and active strategies applied on the building.[85]

82 ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), ANSI/ASHRAE/IES Standard 90.2-2018: Energy-Efficient Design of Low-Rise Residential Buildings.

83 Houri and Korfali, "Residential Energy Consumption Patterns."

84 Central Administration of Statistics (CAS) and International Labour Organization (ILO), Labour Force and Household Living Conditions Survey: (LCHLCS) 2018-2019 Lebanon (Central Administration of Statistics (CAS); International Labour Organization (ILO), 2019).

Daylight Requirements

Heating Load (kWh/m²)

$$= \frac{\textit{Total Heating Energy Consumption (kWh/year)}}{\textit{Building Floor Area } (m^2)}$$

Cooling Load (kWh/m²)

$$= \frac{\textit{Total Cooling Energy Consumption (kWh/year)}}{\textit{Building Floor Area } (m^2)}$$

Finally, the ASHRAE 189.1 sustainable metrics evaluates the environmental impact of this energy use through CO_2 equivalent emissions per m².

For example, an estimated 1.6 tons of CO_2 and 7.3 kg of SO_2 as well as other pollutants are generated per capita in Lebanon annually.[86]

This provides a foundation to compare emissions pre- and post-retrofit and to assess the role of heating energy sources and grid carbon intensity.

85 ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), ANSI/ASHRAE/IES Standard 90.2-2018: Energy-Efficient Design of Low-Rise Residential Buildings.

86 Houri and Korfali, "Residential Energy Consumption Patterns."

04 CASE COMPARISON SETUP

Figure 4.1 - Photography of the Village of Douma, Lebanon

Source: Author's elaboration

4.1 CLIMATE ANALYSIS AND SOLAR POTENTIAL

To analyze Douma's microclimate, the tool Climate Consultant 6.0 was primarily used. The data collected was evaluated and interpreted through a series of graphical representations.

4.1.1 LOCATION

Douma is a traditional town in Mount Lebanon that served as an administrative center during the 19th century Ottoman Tanzimat period. Nearly 70% of its built environment is composed of traditional buildings, the majority of them houses with central halls and characterized by the triple arched facade.

The origins of the town date back to the 18th century, when orthodox Greeks first settled in the northern part of the town, followed by catholic Greeks in the southern part, then finally followed by a Maronites minority. The village saw prosperity in the 19th century due to trade, flourishing in the souks that held around 100 shops, as it had become a crossroad between the coastal towns of Baalbek in Bekaa.

Nowadays, many of the village's vernacular houses remain well maintained, a condition rooted in the population migration of the 1920s and the lack of state-driven development. However, the post-civil war period (1990) saw a wave of unregulated additions to these houses, some of which remain reversible.[87]

87 European Union (MEDA Programme) and Antoine Fischfisch, Douma – CORPUS – Euromed Heritage (Euromed Heritage Programme, MEDA (European Union), 2003).

4.1.2 CLIMATE IDENTIFICATION

The town of Douma is classified as a Csa Mediterranean climate, with temperate (C), dry (s) hot (a) summer according to the Köppen climate classification, and is further categorized as a warm-humid climate zone (3A) by ASHRAE, where zone 3 refers to a generally warm region and A is a humid subcategory.[88] The average annual temperature is 17°C; the warmest month is July with the hottest week falling between 20th to 26th, while the coldest month being January, with the coldest week occurring from 20th to 26th.

Despite this classification, Douma exhibits the distinct characteristics of mountainous climate. As illustrated in Figure 4.1.2.1, the region experiences a high diurnal temperature range, high summer temperatures and cold winters. Figure 4.1.2.2 presents the mean monthly temperature and precipitation, highlighting dry, hot summer months contrasted with cooler, wetter winter periods, typical of high-altitude Mediterranean zones.[89]

88 ASHRAE, NSI/ASHRAE Addendum a to ANSI/ASHRAE Standard 169-2020: Climatic Data for Building Design. Table Annex 1-4.

89 Abdulrahman Madini et al., "Comparative Study on Phenology, Yield and Quality of Iranian Saffron Cultivated in Lebanon and Iran," Fresenius Environmental Bulletin 28 (November 2019): 9655–60.

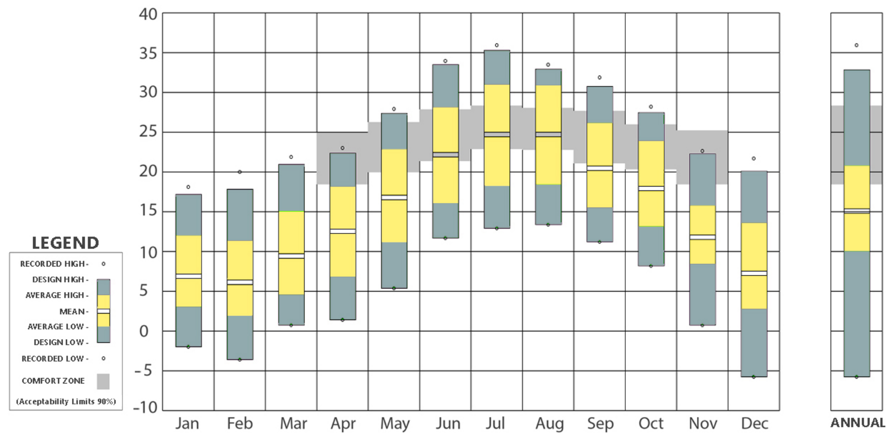


Figure 4.1.2.1 – Temperature Range in Douma, Lebanon

Source: Graph generated by author using Climate Consultant 6.0

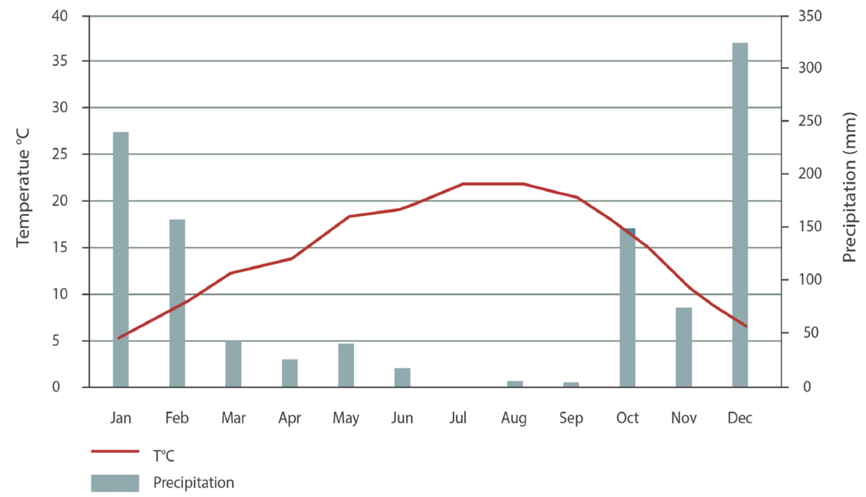


Figure 4.1.2.2- Mean Monthly Temperature and Precipitation in Douma, Lebanon

Source: Adapted from Madini et al. 2019.

To further characterize the local climate, the sun path diagram helps us understand the seasonal angles and inform decisions regarding shading, glazing and passive solar heating strategies (Figure 4.1.2.3).

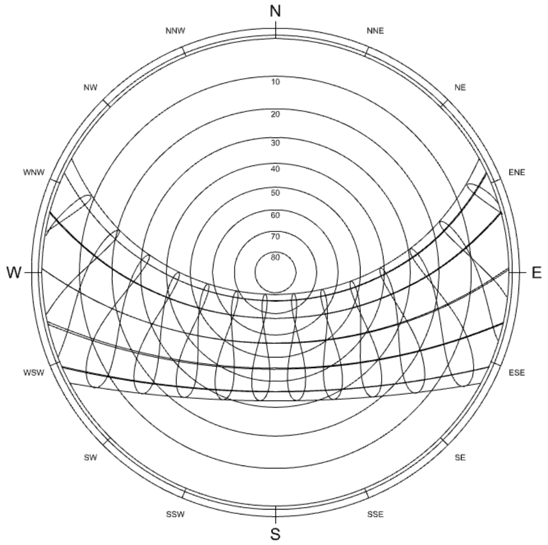


Figure 4.1.2.3 – Sun Path Diagram for Douma, Lebanon

Source: Diagram generated by the author using Ladybug Grasshopper

Moreover, the heating and cooling degree days from various regions in Lebanon were extracted and analyzed to establish and compare the country's diverse climate zones (Figure 4.1.2.4). These values help us quantify the annual heating and cooling demands, thereby helping to define weather patterns and classification. The classification of the following climates was conducted according to both ASHRAE Standard 169-2020 (Figure 4.1.2.1) and the Italian Climate Classification defined by D.P.R. 26 Agosto 1993 n°412, Allegato A, consolidated in 2018 (Figure 4.1.2.2). [90]

Figure 4.1.2.4 illustrates these Lebanese climatic zones together with their respective heating degree days (HDD) and cooling degree days (CDD), proving a comparative overview of regional differences that are translated in building energy demand.

According to the ASHRAE 169-2020 Climatic Data for Building Design Standards, Lebanon has multiple climates mainly determined by its topography. [91]

The coastal plain falls within moist and marine subzones, the medium altitudes of Mount Lebanon where Douma is located correspond to cooler Mediterranean conditions, the Beqaa Valley represents the plateau and drier continental zones, and finally the high altitudes of Mount Lebanon and the Anti-Lebanon range are classified as alpine (Figure 4.1.2.4 and 4.1.2.5).

Based on the HDD set temperature (Heating Degree Days) of 18.3°C and CDD set temperature (Cooling Degree Days) of 10°C, and considering moisture subzones (A: Moist >50-60%, B: Dry, C: Marine), these categories capture the country's climatic diversity (Figures 4.1.2.1 and 4.1.2.2). [92]

90 Governo Italiano, "D.P.R. 26 Agosto 1993, n. 412 – Allegato A (Testo Consolidato 2018)," 1993, https://www.certifico.com/impianti/documenti-impianti/337-documenti-impianti-riservati/7099-zone-climatiche-tabella-a-aggiornata-d-p-r-412-1993.

91 Emilio Sassine et al., "Low-Energy Building Envelope Design in Lebanese Climate Context: The Case Study of Traditional Lebanese Detached House," Energy Efficiency 15, no. 56 (2022), https://doi.org/10.1007/s12053-022-10065-6.

92 ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), ANSI/ASHRAE/IES Standard 90.2-2018: Energy-Efficient Design of Low-Rise Residential Buildings.

Table 4.1.2.1 - Climatic Classifications According to the ASHRAE Standard

Source: Author's compilation based on ASHAR 2018 [92]

STANDARD	ZONE	ZONE TYPE	DESCRIPTION HDD = 18.3°C CDD = 10°C
NSI/ASHRAE AddASHRAE Standard 169-2020	1	Very Hot	5000 < CDD ≤ 6000
	2	Hot	3500 < CDD ≤ 5000
	3	Warm	CDD < 3500 and HDD ≤ 2000
	4	Mixed	CDD < 3500 and 2000 < HDD ≤ 3000
	5	Cool	CDD ≤ 3500 and 3000 < HDD ≤ 4000
	6	Cold	4000 < HDD ≤ 5000

Table 4.1.2.2 - Climatic Classifications According to the Italian Standard

Source: Author's elaboration from Governo Italiano, D.P.R. 26 Agosto 1993.

STANDARD	ZONE	DESCRIPTION HDD =20°C (+ 2°C tolerance)	RECOMMENDED HEATING PERIOD
Italian Climate Classification: Defined by D.P.R. 26 Agosto n. 412 Allegato A consolidated in 2018	A	HDD < 600	1/12 to 15/03 for 6h/day
	B	601 < HDD < 900	1/12 to 31/03 for 8h/day
	C	901 < HDD < 1400	15/11 to 31/03 for 10h/day
	D	1401 < HDD < 2100	1/11 to 15/04 for 12h/day
	E	2101 < HDD < 3000	15/10 to 15/04 for 14h/day
	F	HDD > 3001	No restriction

Figure 4.1.2.4 – Lebanese Climatic Zone with Respective HDD and CDD

Source: Adapted by Emilio Sassine et al. 2022 with additional information by the author

ZONE 1: COASTAL

TRIPOLI

	RESULT	DPR n.412		RESULT	ASHRAE	Heating Period
HDD (20)	1120	C	HDD (18.3)	815	3A	15/11 to 31/03 (10h/day)
CDD (26)	127		CDD (10)	3433		

BEIRUT

	RESULT	DPR n.412		RESULT	ASHRAE	Heating Period
HDD (20)	1182	C	HDD (18.3)	895	2A	15/11 to 31/03 (10h/day)
CDD (26)	151		CDD (10)	3529		

MARJAAYOUN

	RESULT	DPR n.412		RESULT	ASHRAE	Heating Period
HDD (20)	2077	C	HDD (18.3)	1657	3A	1/11 to 15/04 (12h/day)
CDD (26)	64		CDD (10)	2341		

ZONE 2: MEDIUM MOUNTAINS

DOUMA

	RESULT	DPR n.412		RESULT	ASHRAE	Heating Period
HDD (20)	1602	D	HDD (18.3)	1236	3A	1/11 to 15/04 (12h/day)
CDD (26)	103		CDD (10)	2771		

ZONE 3: HIGH MOUNTAINS

BCHARRE

	RESULT	DPR n.412		RESULT	ASHRAE	Heating Period
HDD (20)	2722	E	HDD (18.3)	2266	4A	15/10 to 15/04 (14h/day)
CDD (26)	36		CDD (10)	1918		

HAMMANA

	RESULT	DPR n.412		RESULT	ASHRAE	Heating Period
HDD (20)	2597	E	HDD (18.3)	2139	4A	15/10 to 15/04 (14h/day)
CDD (26)	33		CDD (10)	1936		

ZONE 4: INLAND PLATEAU

RAYAK

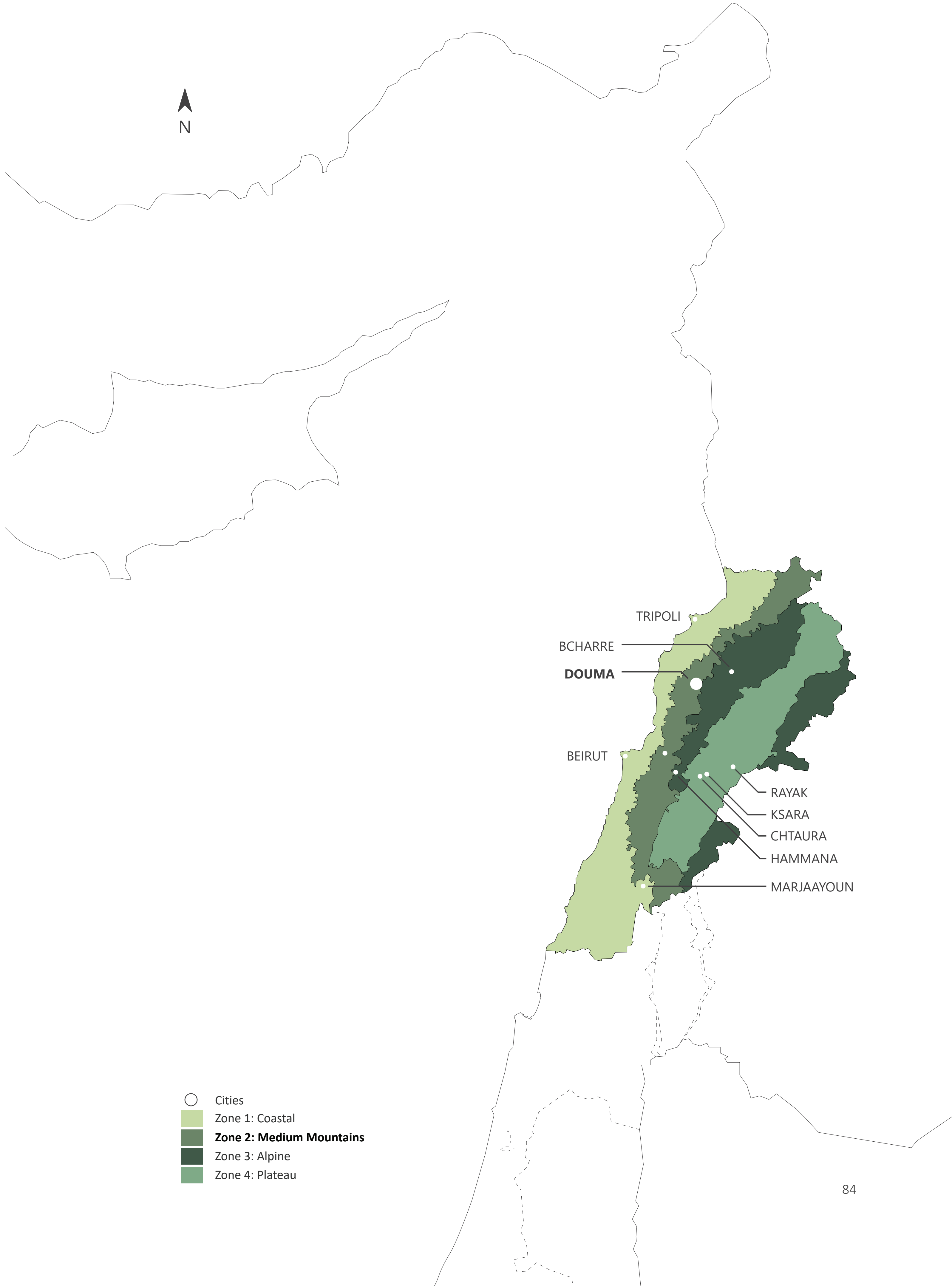
	RESULT	DPR n.412		RESULT	ASHRAE	Heating Period
HDD (20)	3017	F	HDD (18.3)	2557	4A	15/10 to 15/04 (14h/day)
CDD (26)	79		CDD (10)	1924		

KSARA

	RESULT	DPR n.412		RESULT	ASHRAE	Heating Period
HDD (20)	2880	E	HDD (18.3)	2421	4A	15/10 to 15/04 (14h/day)
CDD (26)	51		CDD (10)	1906		

CHTAURA

	RESULT	DPR n.412		RESULT	ASHRAE	Heating Period
HDD (20)	2178	C	HDD (18.3)	1792	3A	15/10 to 15/04 (14h/day)
CDD (26)	225		CDD (10)	2665		



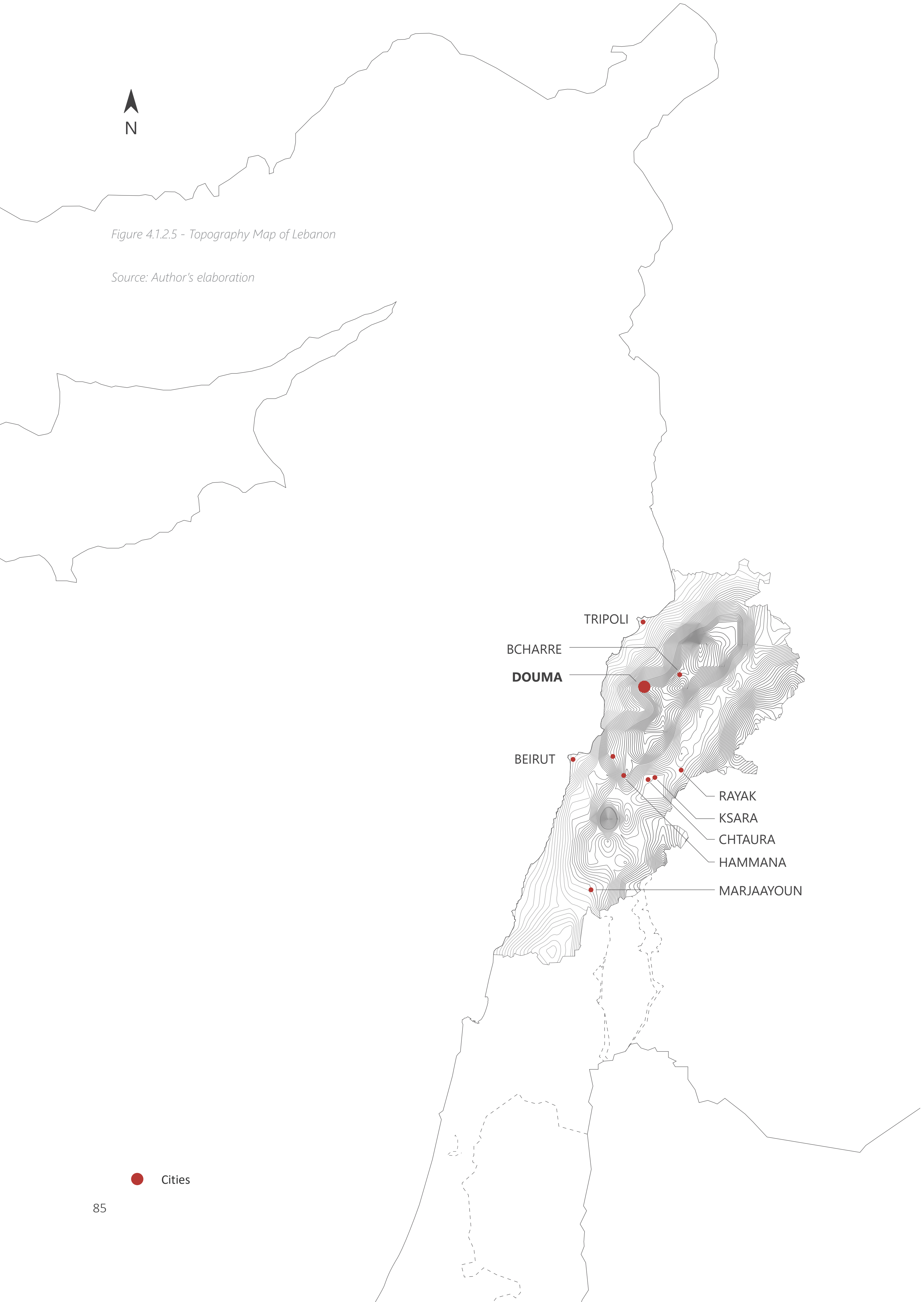


Figure 4.1.2.5 - Topography Map of Lebanon

Source: Author's elaboration

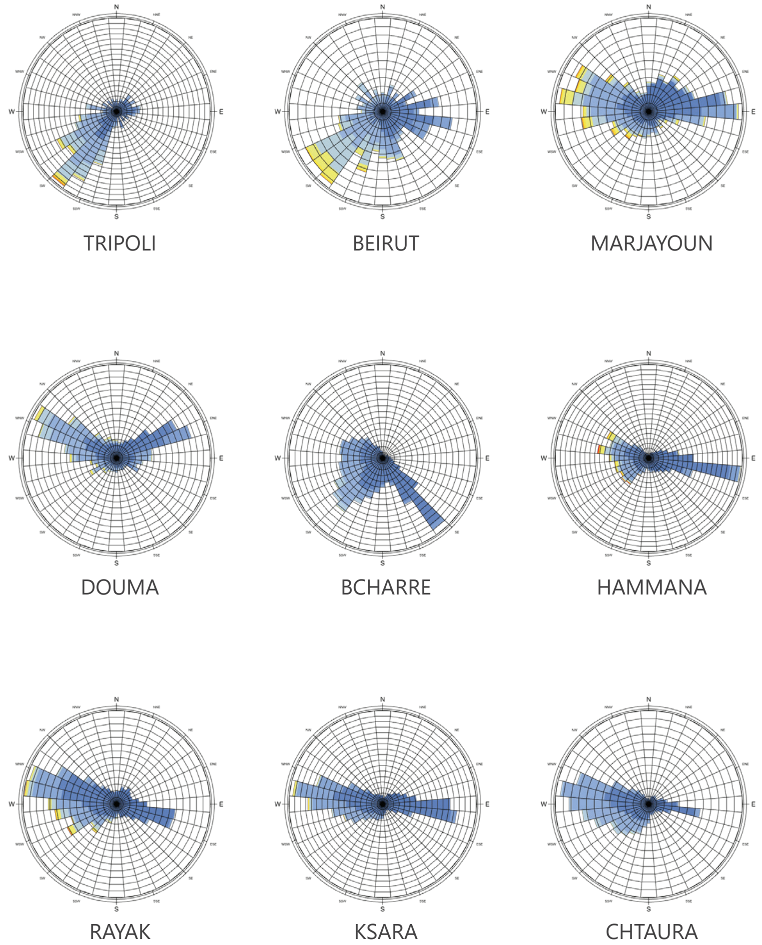
4.1.3 WIND

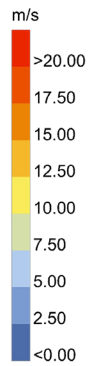
The town of Douma has an average annual wind speed of 2.45 m/s, with the prevailing wind coming from a direction of 300 degrees.

However, as illustrated in Figure 4.1.3.2, which shows monthly wind direction at four-hour intervals, the wind patterns vary seasonally: during the colder months, easterly winds dominate, while in the warmer months, westerly winds prevail. This seasonal shift offers potential for natural ventilation strategies to enhance indoor comfort and reduce reliance on mechanical cooling.

Figure 4.1.3.1 - Wind graphs per climatic zones and per locations

Source: Ladybug, Grasshopper





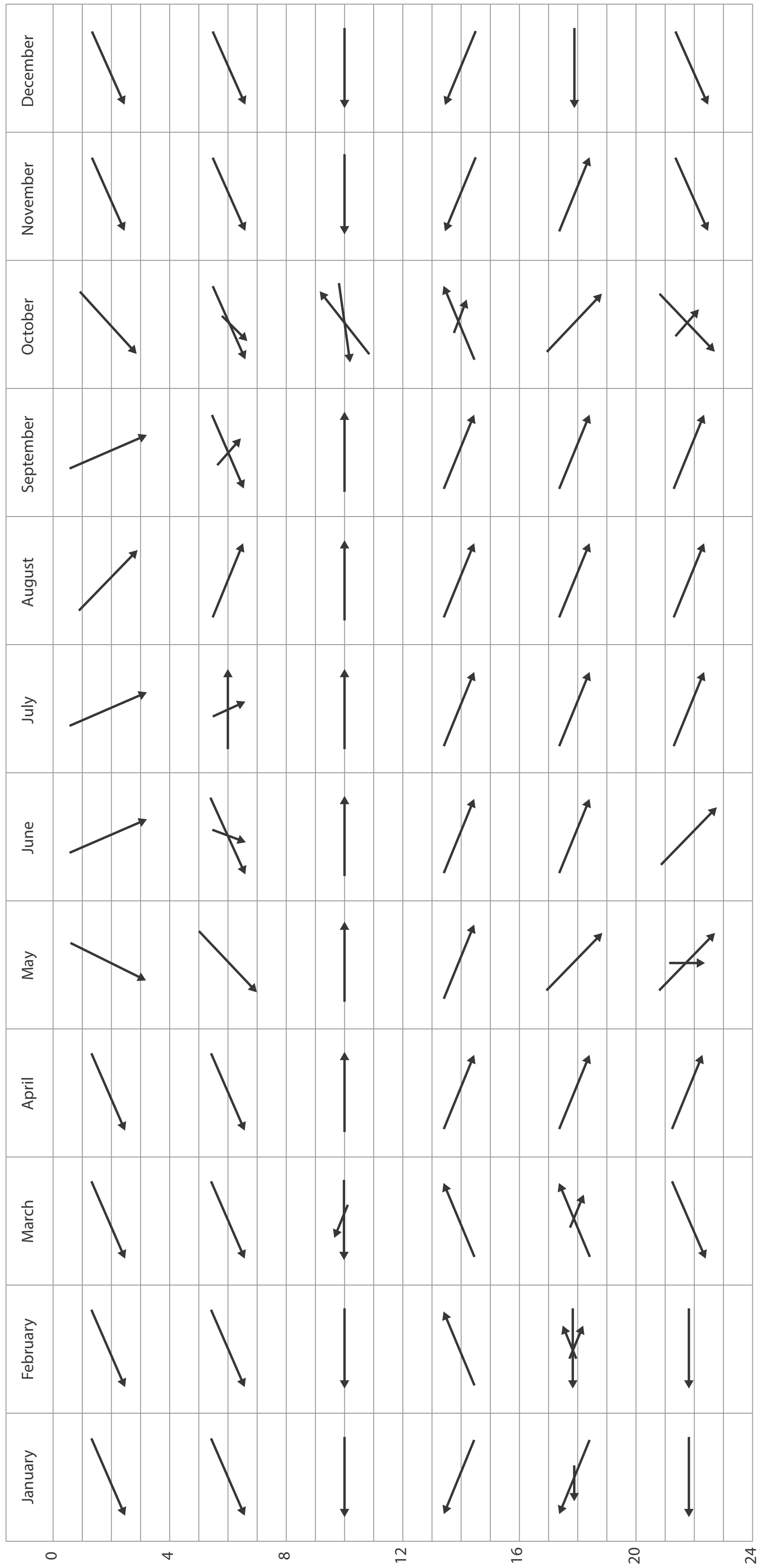


Figure 4.1.3.2 - Prevailing wind by months (4-hours intervals), Douma

Source: Author's elaboration based on the EPW file

4.1.4 SOLAR POTENTIAL

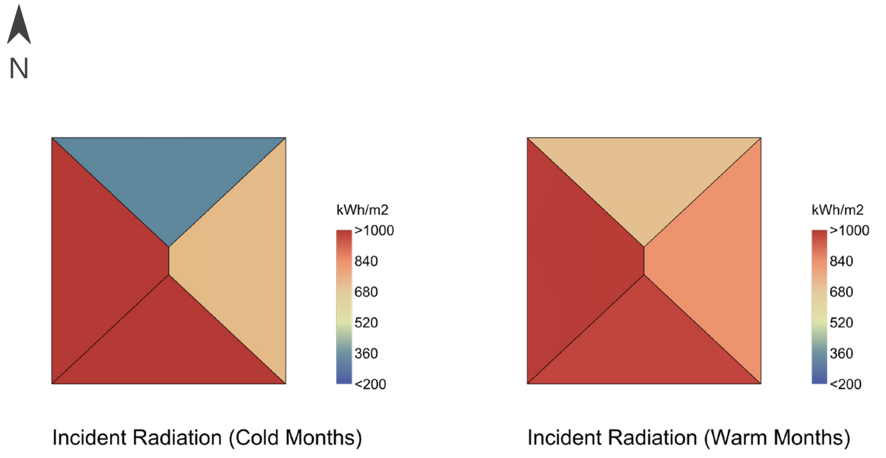
Having established the climatic context and characteristics of the case study location, this subsection expands the scope to examine the potential for transitioning into an off-grid, more reliable and cleaner energy source in Lebanon. A clear understanding of the national energy framework (Section 2.3.1) and the energy problems and needs (Section 2.3.2.) underscores the necessity to evaluate the site's solar potential.

The following analysis presents the annual solar radiation incident on the building envelope extracted from Ladybug on Grasshopper and evaluates the potential photovoltaic (PV) output based on realistic system parameters and orientation.

Figure 4.1.4.1 illustrates the incident solar radiation on the building's roof across two seasonal periods, as defined in the ASHRAE climate zone classification and delimitation of the heating period based on the Heating Degree Days and Cooling Degree Days: the cold months (autumn – winter) that are from November 1st to the April 15th, and the warm months (summer – spring) from the April 16th to the October 31st.

Figure 4.1.4.1 - Seasonal Incident Radiation on the Roof in kWh/m² (Cold and Warm Months)

Source: Author's elaboration from Climate Studio, Grasshopper



Roof area:
North/South Face: 53.2 m²
West/East Face: 64.9 m²

Calculation of the Iicident solar radiation by orientation for the roof (kWh):

For the cold months (heating period from 01/11 to 15/04):

South face:
Total: 49,295.1 kWh/year
Cumulative Rad: 926.4 kWh/m²

West face:
Total: 45,372.8 kWh/year
Cumulative Rad: 683.6 kWh/m²

East face:
Total: 31,599.5 kWh/year
Cumulative Rad: 487.4 kWh/m²

For the warm months (cooling period from 16/04 to 31/10):

South face:
Total: 67,499.2 kWh/year
Cumulative Rad: 1 268.5 kWh/m²

West face:
Total: 81,907 kWh/year
Cumulative Rad: 1 234 kWh/m²

East face:
Total: 66,207.6 kWh/year
Cumulative Rad: 1,021.1 kWh/m²

All year round:

South face:
Total: 116,795.2 kWh/year
Cumulative Rad: 2 195 kWh/m²

West face:
Total: 127 307.5 kWh/year
Cumulative Rad: 1,918.1 kWh/m²

East face:
Total: 97,796.7 kWh/year
Cumulative Rad: 1,508.3 kWh/m²

To assess the viability and effectiveness of solar energy integration at the scale of the building, we must outline the key parameters of the proposed photovoltaic (PV) system and present an estimation of its annual energy input. This data includes data orientation, incident solar radiation, panel efficiency, system losses, and roof surface availability.

By applying a standardized calculation method used in the IEC 61724-1:2021, the PV output potential is quantified according to its orientation and across different seasons.[93] This step is critical to evaluate how much of the building's electricity demand can be offset by solar power generated on-site, and to assess the return on investment (ROI) for small scale, decentralized solar systems in the current energy context of Lebanon.

93 International Electrotechnical Commission (IEC), IEC 61724-1:2021 Photovoltaic System Performance – Part 1: Monitoring, Geneva, Switzerland, 2021.

Solar Potential

PV System Parameters and Output Estimation:

Efficiency (η): 20%
System Losses (L): 14%
G: Total solar radiation on that face (kWh/year)
Gt: Cumulative Incident Radiation (kWh/m2/year)

PV output formula:

Total PV Output (kWh/year) = G x η x (1-L)
PV output per m2 (kWh/m2/year) = Gt x η x (1-L)

Typically, Lebanese households can fit solar installations of 13 to 25 panels of a capacity of 11.2 kWp on the roof, which averages to an investment of around 6000 USD.

To reduce the upfront investment cost, we will be proposing a configuration of 8 solar panels, which brings us to an investment of around $2000 - $2700 US for the average panel price of $90 US (includes inverter, mounting structure, cabling, and labor) and with battery storage that costs around $1000 - $4000 US, depending on size and type.

While solar panels have a life expectancy of around 10 years, annual energy savings would be around $2000 US, making our return on investment (ROI) economically viable and attractive. However, these preliminary assumptions will be re-evaluated in the final analysis chapter, where the simulated energy demand and photovoltaic offset values will be compared to validate the system's effectiveness.

Average PV panel size (60 cell)
= 1m x 1.65m = **1.65 m²**

Efficiency: 17-21%
Panel Power: 350 – 400-Watt peak Wp (=0.4 Kwh)
System losses: 14% typical

Maximum roof panel capacity:

South:
Total area = 53.21 m²

Panel capacity:

$$\frac{53.21\ m^2}{1.65\ m^2} = 28 \text{ panels}$$

West:
Total area = 64.86 m²

Panel capacity:

$$\frac{64.86\ m^2}{1.65\ m^2} = 30 \text{ panels}$$

East:
Total area = 64.86 m²

Panel capacity:

$$\frac{64.86\ m^2}{1.65\ m^2} = 30 \text{ panels}$$

Maximum available panel area per orientation:

South: 1.65 m² x 28 = **46.2 m²**
West: 1.65 m² x 30 = **49.5 m²**
East: 1.65 m² x 30 = **49.5 m²**

Max panel count	Face	Season	kWh/year		
			Radiation	PV Output	Total PV Output
28	S	Warm M	67 499.2	11 609.8	20 088.6
		Cold M	49 295.1	8 478.8	
30	W	Warm M	81 907	14 088	21 892.1
		Cold M	45 372.8	7 804.1	
30	E	Warm M	66 207.6	11 387.7	16 822.8
		Cold M	31 599.5	5 435.1	

Table 4.1.4.1 - Seasonal Total PV Output per Orientation in kWh/year

Max panel count	Face	Season	kWh/m2/year		
			Cum Incident Rad	PV Output	Total PV Output
28	S	Warm M	1 268.5	**218.2**	377.5
		Cold M	926.4	**159.3**	
30	W	Warm M	1 234	**212.2**	329.8
		Cold M	683.6	**117.6**	
30	E	Warm M	1 021.1	**175.6**	259.4
		Cold M	487.4	**83.8**	

Table 4.1.4.2 -Seasonal Total PV Output per Orientation and kWh/m2/year

Source: Author's elaboration

4.2 HOUSE TYPOLOGY AND GENERAL OVERVIEW

4.2.1 DESCRIPTION OF THE CHOSEN TYPOLOGICAL MODEL

The selected case study is a Central Hall House, considered the Lebanese house par excellence and is the best example of the traditional Lebanese residential architecture. This specific house dates back to 1886 as documented by Friedrich Ragette, and is characterized by a symmetrical floor plan, a common feature of the 19th century Lebanese dwellings.[94]

Figure 4.2.1.4 illustrates the ground floor (GF), which accessed via the main entrance on the west façade, facing the valley. An external staircase leads to the first floor as seen in Figure 4.2.1.5, indicating spatial separation between the two levels. The ground floor includes four rooms and two corridors, one along the east and the other forming the west-facing entrance. The first floor mirrors the layout with four rooms surrounding a long central living hall divided by an additional interior arcade. Additional north and south corridors are present, with the southern corridor serving as the main entrance through the stairs. The northern corridor includes a door leading to nowhere – a planning remnant that reflects the traditional intent of extending the house if deemed necessary.

The house is positioned centrally in the plot, and all four facades hold almost equal importance. The ground floor, originally used for storage, could also be used as a seasonal living space, in order to escape the summer heat. Notably, service functions such as kitchen and toilets are not included in the house plan, as they were historically located in the garden; however, they are now often incorporated into the main structure through internal conversion or added extensions.

Architecturally, the ground floor is more enclosed with smaller and fewer rectangular openings which we can notice in Figure 4.2.1.1, while the first floor has larger and more frequent arched windows due to its thinner wall sections. The typical triple arch is oriented westward and connects to a balcony.

The building envelope is composed of multiple masonry layers, and no exterior finishes. The ground floor and first floor west and east walls are made of a 35 cm exterior layer of sandstone, a 40 cm rubble masonry core, and finally a 25 cm interior layer of sandstone with an interior plaster. However, the north

94 Ragette, Architecture in Lebanon: The Lebanese House during the Eighteenth and Nineteenth Centuries.

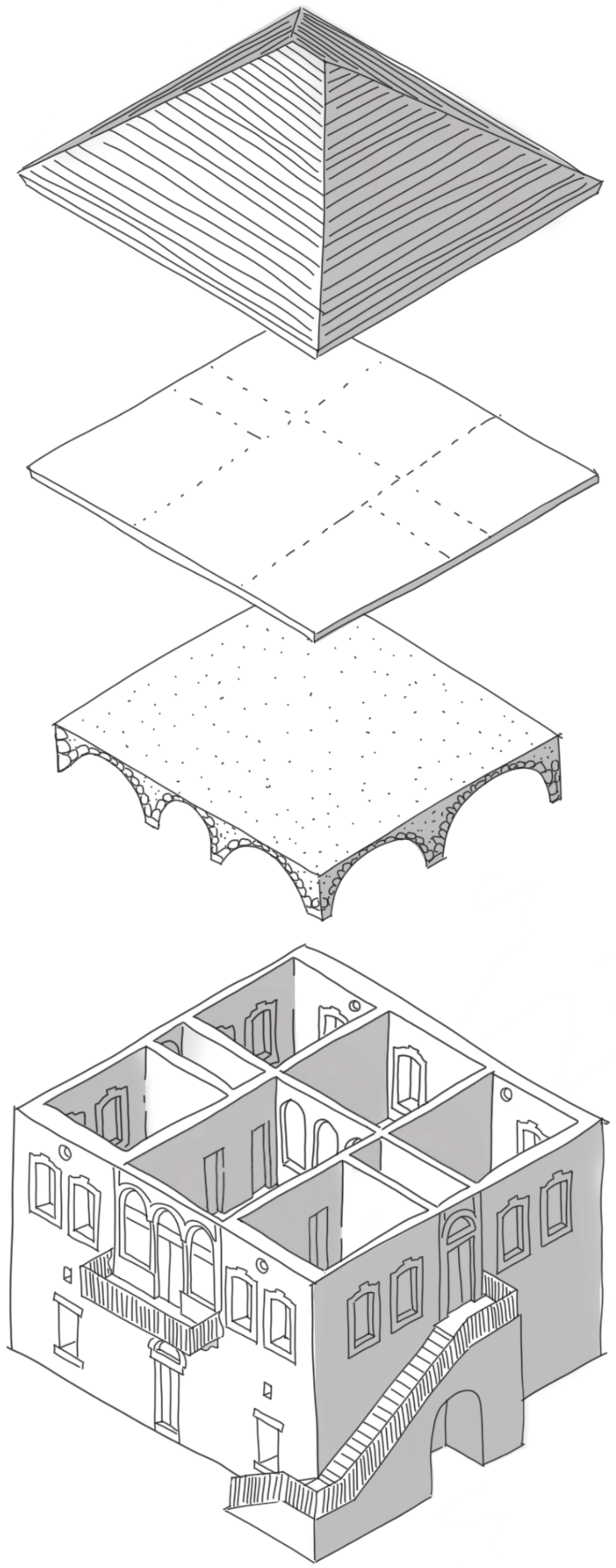


Figure 4.2.1.1 - Central Hall House Exploded

Source: Author's elaboration

and south walls of the first floor are only a single 35 cm sandstone layer and the finishing layer.

The roof is constructed of red terracotta tiles supported by a timber structure, uninsulated and non-habitable, with access only via a trap door and ladder. It is sloped to shed rainwater and snow, since we are in a mountainous region that experiences rainfall and snowfall during the cold months. As seen in section 4.1.4, the roof surface has a capacity to accommodate a maximum of 28 PV panels on the south side and 30 panels on both the west and east sides.

The structural system of the house varies by floor: the ground floor features groin vaults supported by stone piers (Figure 4.2.1.1) – particularly suitable due to the square geometry of the rooms. A sand and screed layer separates it from the first floor, which uses traditional terracotta tiles. The ceiling height is 4.8 m on the ground floor and 4.5 m on the upper level.

The house's heating is provided by a traditional wood-fueled Sobia stove (Figure 4.2.1.2 and 4.2.1.3), located in the central hall of the first floor. It offers radiant heating to the adjacent rooms, which typically keep the doors open in the winter. Cooling is entirely passive, employing high-level ventilation openings or Taqat, large windows, and the triple arch as a wind input. Natural ventilation is achieved through strategic window and door openings, common in traditional Lebanese practice.

Shading and light control are provided by the double-leaf wooden louvered shutters, paired with arched windows on the first floor and rectangular windows on the ground floor. The interior finishes include stone or tiled flooring and rubble masonry walls. The ground floor is structurally load-bearing, while the upper floor partitions are made of wooden framing filled with rubble, finished with plaster – a common technique in traditional upper floors.

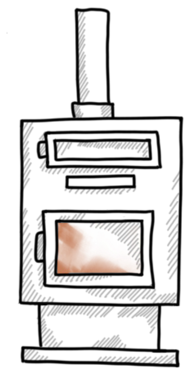


Figure 4.2.1.2 - Traditional Sobia Stove (Wood-Fueled)

Figure 4.2.1.3 - Picture of a Traditional Sobia Stove (Wood-Fueled)

Source: Author's elaboration

Figure 4.2.1.4 - Ground Floor Plan, scale 1/100

Source: Author's elaboration

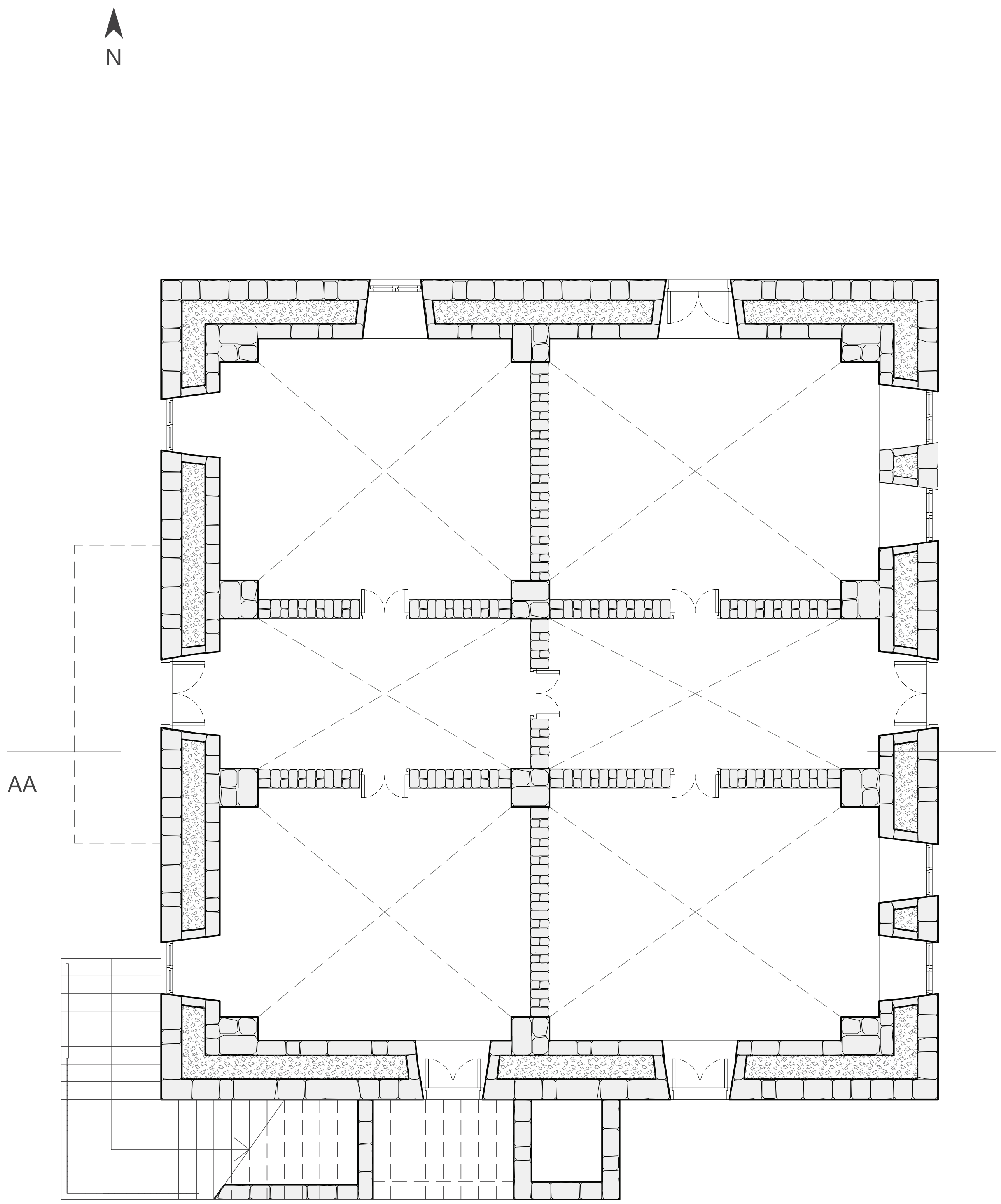


Figure 4.2.1.5 - First Floor Plan, scale 1/100

Source: Author's elaboration

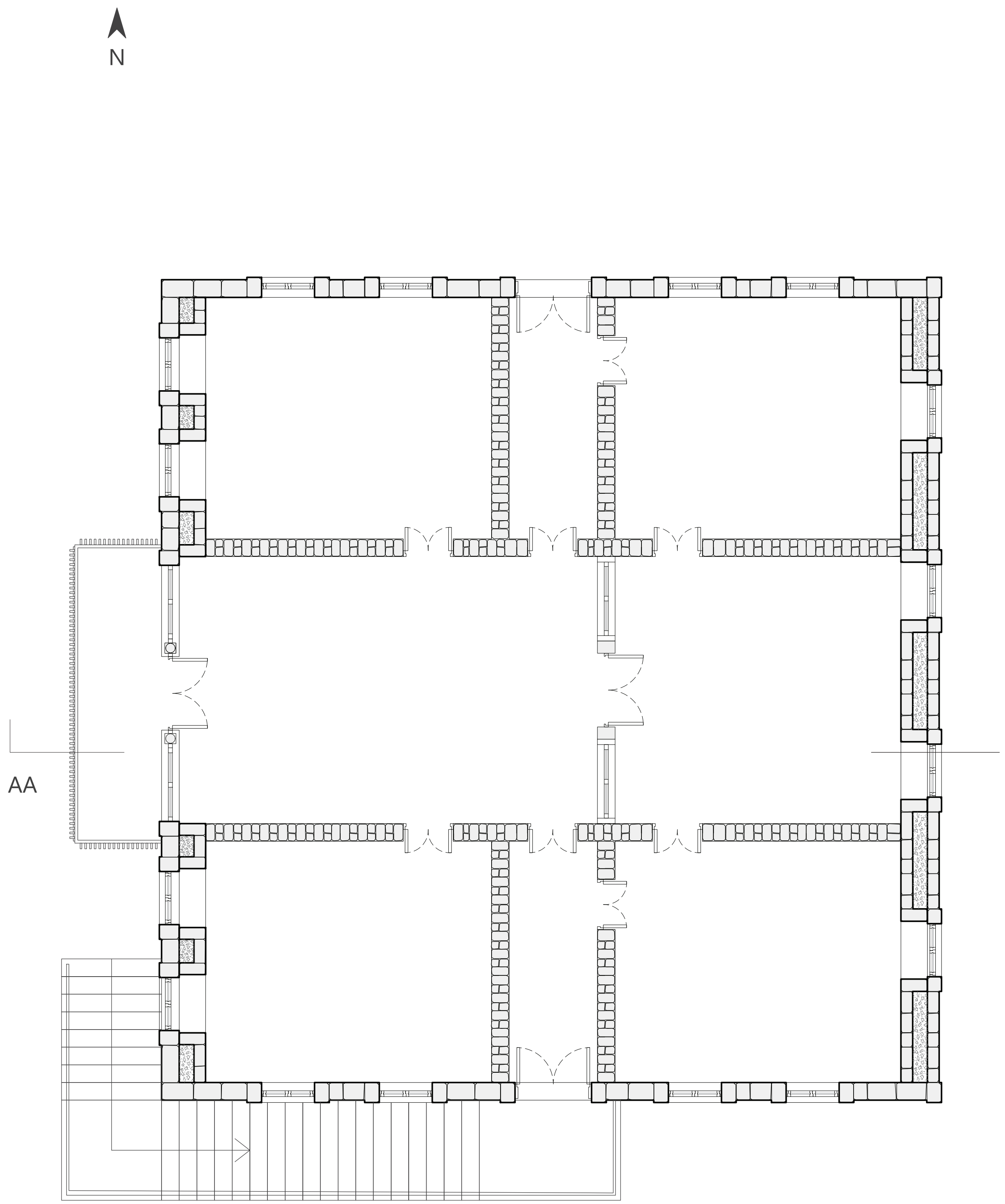
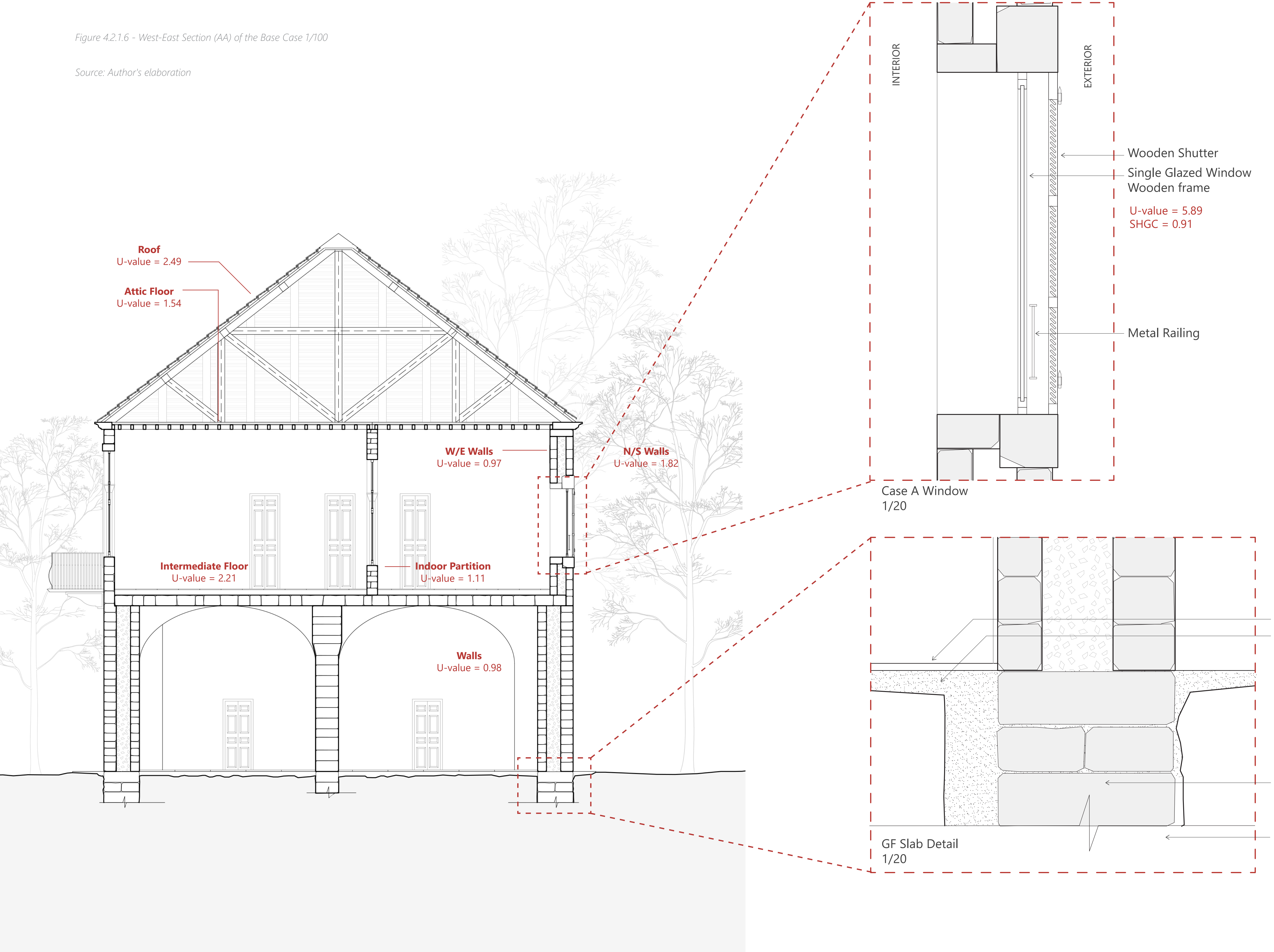


Figure 4.2.1.6 - West-East Section (AA) of the Base Case 1/100

Source: Author's elaboration



4.2.2 OCCUPANCY PATTERNS

In order to accurately assess indoor environmental quality and thermal comfort, it is essential to establish and understand occupancy patterns of the case study house. As a single-family dwelling, the house is typically inhabited by an average of 4 occupants (rounded average of 3.8) [95], whose presence and activity levels vary significantly throughout the day. These fluctuations in occupancy not only affect internal heat gains and ventilation needs but also influence comfort perception and the demand for heating and cooling.

Occupancy modeling for the house is based on a daily cycle of 13 occupied hours on average (including weekdays and weekends), amounting to a total of 4745 hours annually. The data is structured into five distinct time periods of different occupancy activities and is represented as a fractional schedule from 0 (unoccupied) to 1 (full occupancy).

From Midnight to 6:00, the occupancy remains at a constant of 0.6, accounting for sleep schedules or uneven occupancy in different rooms of the house. Between 6:00 to 9:00, the occupancy increases to 0.9, indicating a higher occupancy in the morning due to morning routines and preparations for work or school. During the daytime period from 9:00 to 17:00, the occupancy drops to almost 0, suggesting the space is largely unoccupied, typically corresponding to typical working or school hours. However, since the same schedule is applied throughout the week - including the weekend - the baseline occupancy is raised to 0.2 to account for occasional presence. In the early evening from 17:00 to 21:00, occupancy increases to 0.8, suggesting the return of residents and evening domestic activity. Finally, from 21:00 to Midnight, occupancy decreases again to 0.4, reflecting a gradual winding down of activity as residents prepare for sleep.

95 Central Administration of Statistics (CAS) and International Labour Organization (ILO), Labour Force and Household Living Conditions Survey.

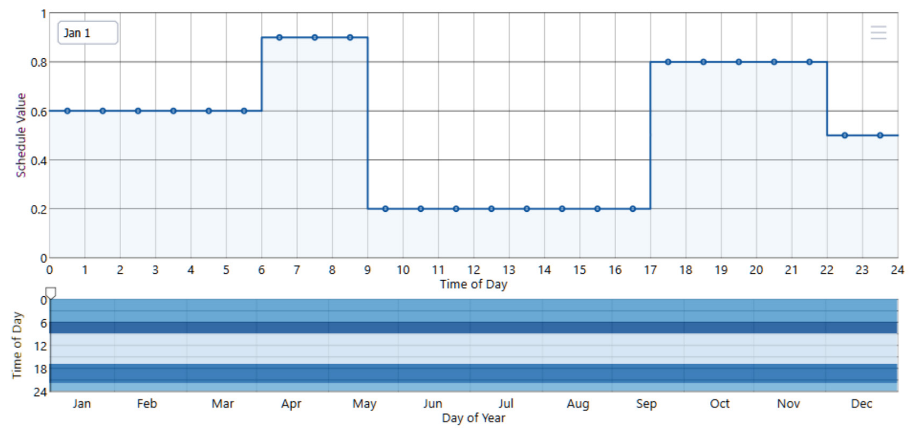


Figure 4.2.2.1 – Daily Occupancy Schedule

Source: Author's elaboration from Climate Studio, Grasshopper

4.2.3 THERMAL PROPERTIES OF CONSTRUCTION MATERIALS

To accurately assess the building's thermal performance and simulate its energy demand and comfort level in Grasshopper and Climate Studio, we conducted a comprehensive analysis of the thermal properties of the construction materials. The thermal behavior of the building envelope – including walls, floors, roof, and windows – directly impacts heat transfer, indoor temperature regulation and the overall energy efficiency.

Table 4.2.3.1 details the properties of the glazing systems, including U-values, solar heat gain coefficient (G-value), visible transmittance (T-vis), and frame conductance. [96]

construction is not uniform – the north and south facades differ in composition and thickness from the west and east facades – a weighted average U-value was calculated to represent the overall thermal transmittance of the envelope more precisely. This ensures that the model reflects the heterogeneity of the building's construction and provides us with more reliable simulation results.[100]

First, we determine the distributed façade area only on the first floor and calculate its total area.

According to the EN ISO 6946:2017,[101] standard surface thermal resistance is applied for

96 "Windows — ClimateStudio Latest Documentation," accessed August 4, 2025, https://climatestudiodocs.com/docs/thermal_window.html.

97 Solemma, "ClimateStudio," Solemma, https://www.solemma.com/climatestudio.

98 Historic England, Energy Efficiency and Historic Buildings: Insulating Solid Ground Floors.

99 David Pickles, "Energy Efficiency and Historic Buildings: Insulating Solid Walls."

Table 4.2.3.1 - Window and Glazing Properties

Source: Author's elaboration

TYPE	DIMENSIONS	Thermal Transmittance (U-value) W/m².K	Solar Heat Gain Coefficient (SHGC)	Visible Transmittance (Tvis)	Frame Conductance W/m².K
Single Glazing		5.894	0.905	0.913	
Wood	7 cm				2 cm

A separate Table 4.2.3.2 summarizes the physical and thermal characteristics of each envelope component. It includes material density, thermal conductivity (λ), thermal transmittance (U-value), and specific heat capacity (c).[97 98 99]

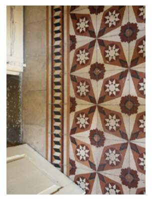
Given that the first-floor wall

internal and external air layers, with the following values:

R_{EXT} = 0.04 m².K/W
R_{INT} = 0.13 m².K/W

Since the walls are not uniformly constructed, the east and west walls feature a multilayered

100 International Organization for Standardization, ISO 6946:2017 Building Components and Building Elements — Thermal Resistance and Thermal Transmittance — Calculation Methods, ISO, 2017, https://www.iso.org/standard/65708.html.

	USE	DESCRIPTION	MATERIAL	DIMENSIONS	Density kg/m³	Thermal Transmittance (U-value) W/m²K	Thermal Conductivity W/m²K	Thermal Mass kJ/m³K	Specific Heat Capacity Cp J/kg.K
GF: U-val = 0.98 W/m².K 1st Floor U-val = 1.82 W/m².K	WALLS		Sandstone	35 cm	1920	2.82	1.90	1516.8	790
			Rammed Earth fill	40 cm	1730	1.40	0.75	1522.4	880
			Sandstone	25 cm	1920	3.32	1.90	1516.8	790
	PLASTER	*optional finishing*	Int. Plaster	1 cm	900	5.47	0.77	1800	1800
U-val = 1.11 W/m².K	PARTITION	*Int. wall*	Sandstone	10 cm	1920	1.41	1.90	1516.8	790
U-val = 2.21 W/m².K	INTERMEDIATE FLOOR		Tiles (Ceramic)	2 cm	1290	5.36	1.20	1260	1260
			Rammed Earth and Sand fill	15 cm	2080	3.66	1.45	748.8	900
			Stone Groin Vaults	30 cm	1920	2.32	1.90	1600	1600
	WINDOWS & DOORS	 	Wood	7 cm	520	1.41	0.13	1600	1600
U-val = 2.49 W/m².K	ROOF		Terracotta Tiles	1.5 cm	1290	3.25	0.75	1260	1260
			Timber Construction	20 cm	520	9.26	9.26	9.26	9.26
U-val = 2.79 W/m².K	GF SLAB		Tiles (Ceramic)	2 cm	1290	5.36	1.20	1260	1260
			Screed	5 cm	2000	4.72	1.2	1000	1000
			Stone Foundation	100 cm	1920	1.43	1.90	1516.8	790

101 International Organization for Standardization, ISO 6946:2017 Building Components and Building Elements — Thermal Resistance and Thermal Transmittance — Calculation Methods, 69.

102 International Organization for Standardization, ISO 6946:2017 Building Components and Building Elements — Thermal Resistance and Thermal Transmittance — Calculation Methods, 6.

102 International Organization for Standardization, ISO 6946:2017 Building Components and Building Elements — Thermal Resistance and Thermal Transmittance — Calculation Methods.

Table 4.2.3.2 - Construction Material Properties (Left)

Source: Author's elaboration

Table 4.2.3.3 - Exterior Wall Area Distribution by Orientation on the 1st floor (Right)

Source: Author's elaboration

construction similar to the ground floor. However, the south and north façades are composed of a single sandstone layer. The following calculation breaks down the R-value for each orientation and derives the overall U-value accordingly.

Total R-value = REXT + R-value of materials + RINT

Following the R-value formula[102], we can use the conductivity values found in Table 4.2.3.1 to determine the individual R-value, and then we can calculate the total R-value of the wall per orientation.

$$\textbf{R-value} = \frac{\textit{thickness (m)}}{\textit{conductivity } (\lambda)}$$

Calculation of the R-values of the walls:

R-val East/West walls =

REXT + RSANDSTONE + RGRAVEL FILL + RSANDSTONE + RPLASTER + RINT

$$R_{EW} = 0.04 + \frac{0.35}{1.90} + \frac{0.40}{0.75} + \frac{0.25}{1.90} + \frac{0.01}{0.77} + 0.13$$

R-val EW = 1.032 m2.K/W

	AREA m² (2 walls)	Total Area m² (4 walls)
East/West	124.2	255.2
North/South	131	

R-val North/South walls = REXT + RSANDSTONE + RPLASTER + RINT

$$R_{NS} = 0.04 + \frac{0.35}{1.90} + \frac{0.01}{0.77} + 0.13$$

R-val NS = 0.367 m2.K/W

We then determine the U-value following the formula given to us by the EN ISO 6946[103]:

$$U\text{-val} = \frac{1}{R\text{-Val}}$$

$$U\text{-val}_{EW} = \frac{1}{1.032}$$

U-val EW = 0.97 W.m².K

$$U\text{-val}_{NS} = \frac{1}{0.367}$$

U-val NS = 2.72 W.m².K

Finally, we determine the weighted average of the 1st floor using both U-values calculated previously, and get a weighted average U-value for the 1st floor of 1.82 W/m².K.

1st Floor Average U-val

$$= \frac{(U_{NS} \times Area_{NS})+(U_{EW} \times Area_{EW})}{Total\ Area\ (m^2)}$$

$$= \frac{(0.97 \times 131) + (2.72 \times 124.2)}{255.2}$$

1st Floor Average U-val = 1.82 W/m².K

4.2.4 OUTDOOR COMFORT AND UTCI

In climate responsive design, outdoor thermal conditions play a critical role in shaping the indoor comfort of buildings when passive strategies are employed for heating or cooling. In traditional massive buildings such as our case study in Douma, Lebanon, the potential for passive strategies is high, and the ability to regulate indoor temperature without active systems is directly influenced by outdoor conditions. Therefore, assessing outdoor thermal conditions in this case is essential to evaluate the efficiency of passive systems such as natural ventilation, solar heat gain and thermal mass performance.

Having examined the percentage of time during which outdoor conditions are thermally comfortable under different conditions, we explore the combinations of sun and wind exposure and turn to a more detailed analysis using the Universal Thermal Climate Index (UTCI). This metric provides a comprehensive measure of outdoor thermal stress by accounting for Dry Bulb Temperature, Mean Radiant Temperature (MRT), Relative Humidity (RH) and Wind Speed.

Four different scenarios were modeled and presented in figure 4.2.4.1.

1- Sun and Wind:
Full climatic input using dry bulb temperature, MRT, RH and wind speed.

2- Sun and No Wind:
Solar influence without ventilation, highlighting passive solar gain.

3- No Sun and No Wind:
Inert environmental conditions, neither radiation nor wind.

4- No sun and Wind:
Highlights wind-driven cooling in shaded conditions.

Each scenario offers a different insight into seasonal passive performance and thermal comfort. Notably, the “No sun and Wind” configuration is the most effective in summer, emphasizing on shading and ventilation for cooling.

This is further illustrated by the diurnal temperature variation (ΔT) in Figure 4.1.2.1 (Section 4.1.2) reproduced in Figure 4.2.4.2, which shows significant temperature swings between day and night. These fluctuations reinforce the importance of thermal mass in buffering indoor conditions and shed the light on other passive strategies such as night flushing the heat out.

At first glance the “No Sun and No Wind” scenario appears more comfortable throughout the year, but its consistent coldness undermines comfort when heat retention is most needed. In

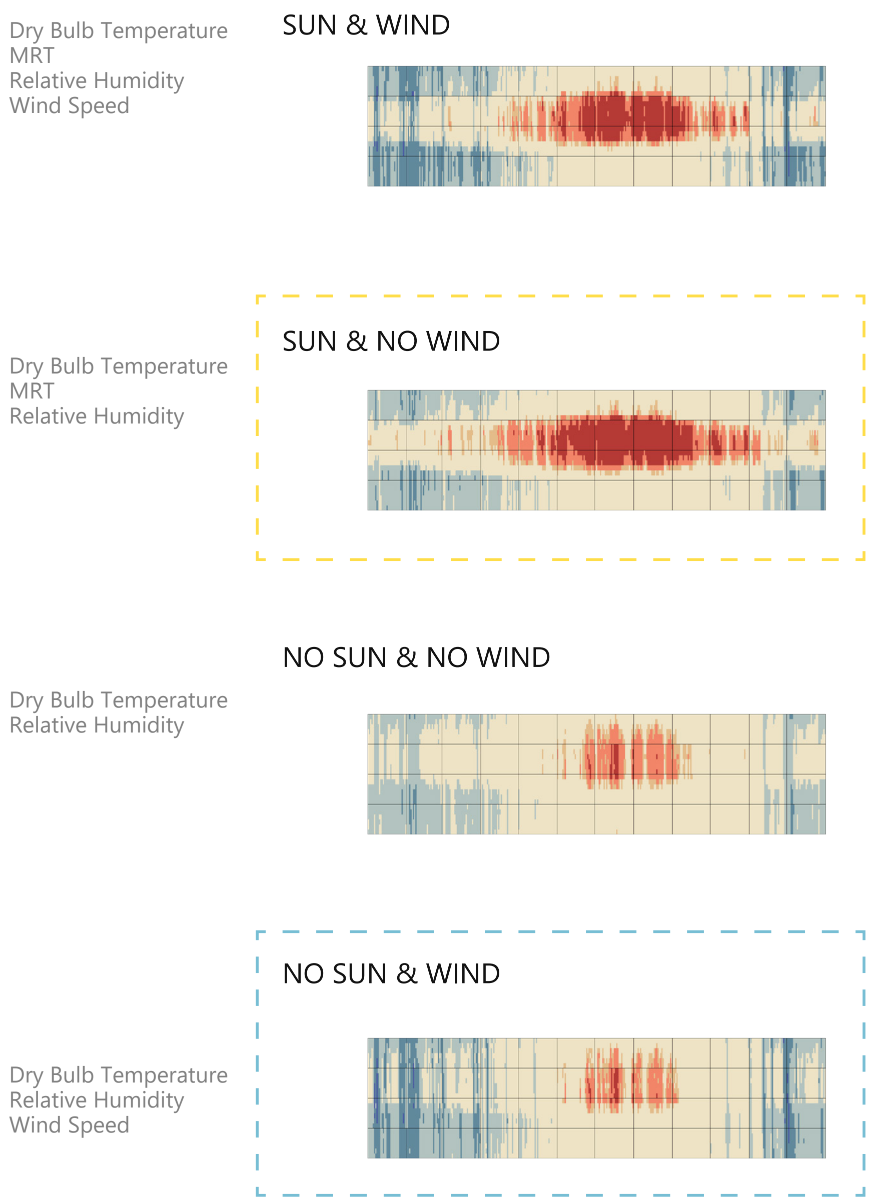


Figure 4.2.4.1 - Thermal Condition (UTCI) in different scenarios in Douma, Lebanon

Source: Author's elaboration from Climate Studio, Grasshopper contrast, the "Sun and No Wind" configuration has better thermal comfort in winter, since solar heat retained by the building's thermal mass is absorbed and gradually released inside the space, helping in passive heating especially in colder hours.

At first glance, both the configurations "Sun and No Wind" and "No Sun and No Wind" appear to provide better thermal comfort than the other scenarios. However, both still exhibit cold stress at night and during early mornings. In the "Sun and No Wind" case, thermal stress is reduced around midday – showing a slight heat starting as early as February – suggesting that solar radiation contributes positively during the day. Yet this solar gain is insufficient to fully counteract nighttime cold.

This pattern can be attributed to the thermal mass behavior of the building, also known as thermal lag, where the thick masonry walls require time to absorb and release heat in the space.

In contrast, the "No Sun and No Wind" scenario consistently underperforms, with persistent cold stress throughout the day. This outcome undermines the importance of solar gain for winter comfort, as the lack of sunlight eliminates the potential for passive heating.

In conclusion, while both scenarios show similar overall comfort trends, the presence of solar radiation – particularly the "Sun and No Wind" case - offers an advantage by regulating indoor thermal conditions through passive solar heating, supported by the thermal inertia of the traditional sandstone construction.

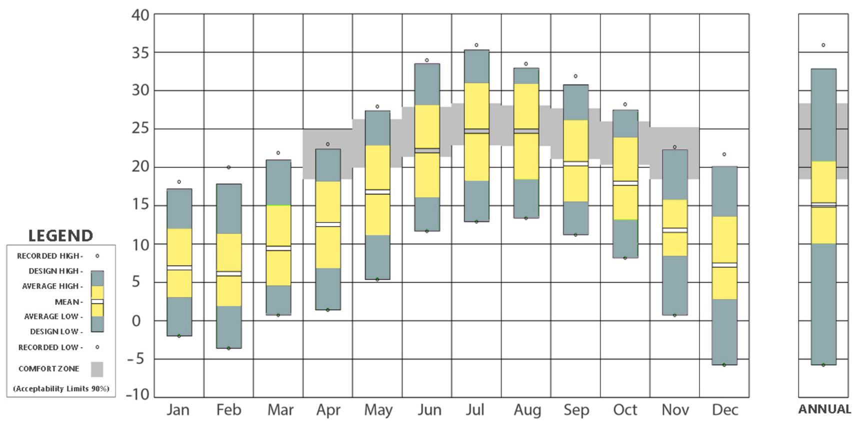


Figure 4.2.4.2 – Temperature Range in Douma, Lebanon (reproduced from Figure 4.1.2.1)

Source: Graph generated by author using Climate Consultant 6.0

4.2.5 SOLAR RADIATION AND PASSIVE HEATING

Upon understanding the house's architectural features and thermal behavior, it's important to evaluate solar orientation effects on passive heating during the cold months, as well as vulnerability to overheating in the warm months.

The first step is to determine which solar orientations are beneficial or harmful, since orientation plays a critical role in enhancing thermal comfort or contributing to thermal stress. To do this, we must clarify the primary thermal needs of the building: cooling vs. heating. This orientation-specific analysis will inform design decisions, such as the efficiency of shading devices, and glazing type, and seasonal ventilation strategies.

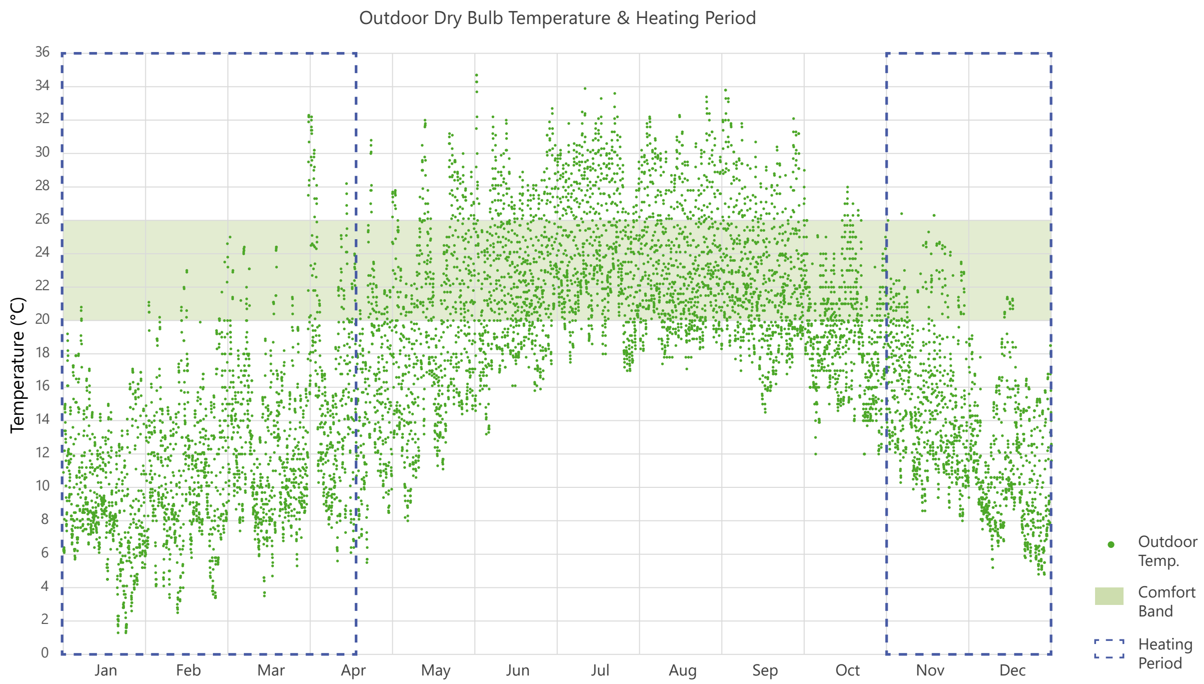
A necessary first step to determine the latter is to cross-reference outdoor air temperature data with solar gains to define the periods of overheating and underheating (Figure 4.2.5.1). Based on the Csa (Mediterranean) climate classification of Douma (Section 4.2.1), the following seasonal needs can be recognized:

Underheating Season:
1/11 to 15/04 – characterized by cold days and nights

Overheating Season:
16/04 to 31/10 – characterized by cool nights and warm days

Figure 4.2.5.1 – Dry Bulb Temperature and Overheating Period Graph

Source: Author's elaboration



This second step involves conducting a solar radiation analysis to assess solar exposure per orientation and season (Figure 4.2.5.2).

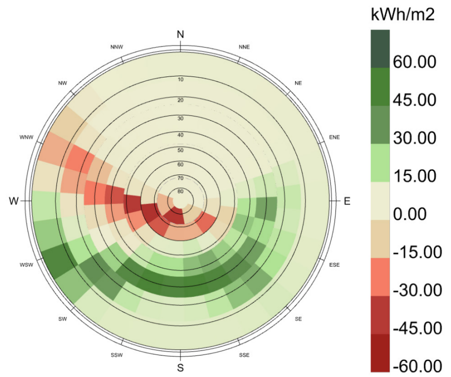


Figure 4.2.5.2 – Annual Total Radiation Benefit/Harm

Source: Author's elaboration from Ladybug, Grasshopper

As each façade orientation is exposed to changing levels of solar radiation throughout the year, this affects both thermal performance and visual comfort. Thus, a detailed solar radiation analysis helps identify which façades are most exposed during the summer when solar exposure is harmful, and during the winter, when it is needed.

By mapping total solar radiation by orientation and by season, we can determine which orientations receive the most solar exposure and when throughout the year.

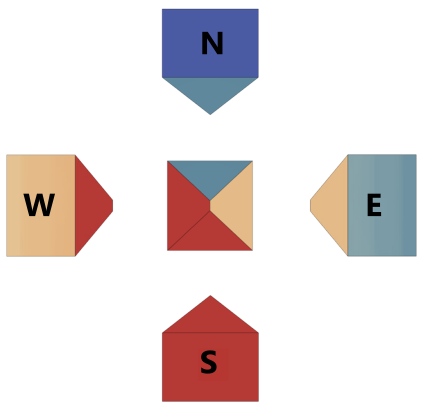
Paired with a thermal performance analysis, a comfort analysis (Section 4.4), and a daylight analysis (Section 4.3.2) we can then evaluate overall performance throughout the year and ensure minimal visual and thermal discomfort, particularly in frequently occupied zones.

The combined results are compared by orientation to identify the façades most affected and in need of intervention. Thus, targeted design strategies can be defined such as installation of shading devices (e.g., overhangs, louvers), selection of appropriate glazing, and seasonal ventilation and operability strategies.

To calculate solar radiation on façade the grasshopper simulation results are based on:

- UNI 8477/1:1983 (Italian technical standard)[104]
- ASHRAE fundamentals Chapter 14[105]
- PVGIS solar irradiance (PV related metrics)[106]

As illustrated in figure 4.2.5.3 and 4.2.5.4, angled planes (roof) collect the most solar radiation in summer, up to four times more than a south window, and the east and west up to twice as much as a south window.



Underheating Period (1/11 to 15/04)

Figure 4.2.5.3 - Cold Months (Heating Period) Solar Radiation on Facades

Source: Author's elaboration from Ladybug, Grasshopper

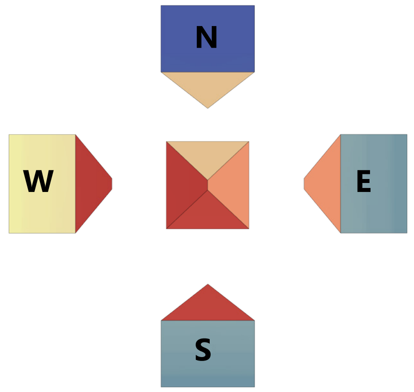
104 Ente Nazionale Italiano di Unificazione (UNI), UNI 8477/1:1983 – Calcolo degli apporti per applicazioni in edilizia. Valutazione dell'energia raggiante ricevuta (Milano, Italy, 1983).

105 ASHRAE, ASHRAE Handbook - Fundamentals.

106 European Commission, Joint Research Centre (JRC), "Photovoltaic Geographical Information System (PVGIS)," European Commission PVGIS, https://ec.europa.eu/jrc/en/pvgis?utm_source=chatgpt.com.

Figure 4.2.5.4 - Warm Months (Cooling Period) Solar Radiation on Facades

Source: Author's elaboration from Ladybug, Grasshopper



Overheating Period (16/04 to 31/10)

Since the roof is completely inhabitable as is used as a storage space, our focus must shift toward balancing the solar radiation coming from the East and West which are the two main façades of the building.

It is generally ruled that east and west orientations are generally not adequate for passing solar heating and pose challenges from a cooling perspective. In contrast, south-facing windows offer advantages as they can be easily shaded during summer and are highly effective for passive solar heating in winter.

In conclusion, during the colder months, solar radiation is generally beneficial, as seen in Figure 4.2.5.5. The southern orientation provides the most effective solar gains for passive heating, as for the east and west façades they also contribute on a smaller level, depending on the time of day and solar altitude (Figure 4.2.5.5 and Tables 4.2.5.1 and 4.2.5.2).

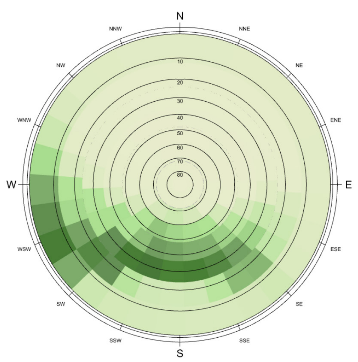
However, during the warm months most solar radiation tends to be harmful, especially from the western façade in the afternoon (Figure 4.2.5.6). On that note, the eastern façade provides slight thermal benefits in the early morning, due to cooler nighttime temperatures.

Furthermore, solar altitudes exceeding 25–30° are especially responsible for overheating, thus the need for targeted shading solutions (Figure 4.2.5.6; Tables 4.2.5.3 and 4.2.5.4).

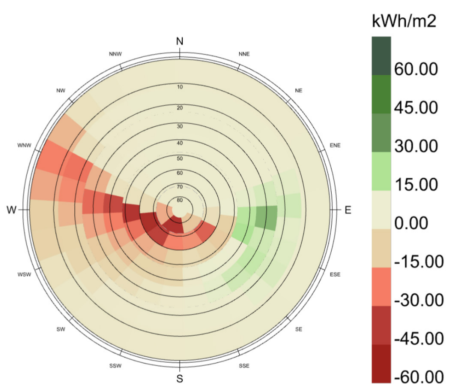
Figure 4.2.5.5 - Cold Months (Heating Period) Total Radiation: Benefit/Harm (left)

Figure 4.2.5.6 - Warm Months (Cooling Period) Total Radiation: Benefit/Harm (right)

Source: Author's elaboration from Ladybug, Grasshopper



Underheating Period (1/11 to 15/04)



Overheating Period (16/04 to 31/10)

	Average Incident Radiation kWh/m2
NORTH	**208.2**
SOUTH	**926.4**
EAST	**683.6**
WEST	**487.4**

Table 4.2.5.1 – Average Incident Radiation Per Orientation for the Cold Months (Heating Period)

Source: Author's elaboration

Season	Time of Day	Orientation	Solar Altitude (°)
Winter	morning	ESE to SE	30 to 60
	mid-day	S	25-60
	afternoon	SSW to SW	50 to 20

Table 4.2.5.2 – Beneficial Solar Exposure for the Cold Months (Heating Period)

Source: Author's elaboration

	Average Incident Radiation kWh/m2
NORTH	**821.7**
SOUTH	**1 268.5**
EAST	**1 234**
WEST	**1 021.1**

Table 4.2.5.3 – Average Incident Radiation Per Orientation for the Warm Months (Cooling Period)

Source: Author's elaboration

Season	Time of Day	Orientation	Solar Altitude (°)	Sun shading need
Summer	morning	ESE	40	Vertical fins
	midday	S to SSW	50-80	Horizontal overhang + vertical fins
	afternoon	WNW	70-30	Vertical fins

Table 4.2.5.4 – Harmful Solar Exposure for the Warm Months (Cooling Period)

Source: Author's elaboration

4.3 CASE A - TRADITIONAL HOUSE (PRE-INTERVENTION)

This section concludes the analysis in 4.2.1 by examining the traditional house in its adaptive passive state, devoid of any active heating systems. This will enable us to understand how the structure alone responds to environmental conditions, without the influence of occupancy, internal heat gains, or mechanical interventions. By modeling the house as an unoccupied and unconditioned space, the simulation isolates the impact of material properties and vernacular design on the indoor thermal comfort. This approach helps us evaluate the thermal performance of the unrestored envelope, focusing on the impact of thermal mass, ventilation potential, and solar exposure on the comfort in different climatic conditions.

4.3.1 PASSIVE STRATEGIES AND ADAPTIVE COMFORT ANALYSIS

Traditional Lebanese houses showcase a characteristic westward orientation, often facing the Mediterranean Sea or valleys. This is the case of the case-study house in Douma. This strategic orientation, discussed in detail in section 4.2.1, reflects considerations and represents an essential passive design strategy. Its goal is to provide a scenic view towards the valley and optimize natural ventilation by capturing prevailing breezes and the valley's natural air corridors that enhance cross-ventilation within the house.

The house's westward position maximizes daylight penetration and creates a strong connection with its context enhancing the indoor living environment (section 4.2.1). The triple arch strengthens this connection to the context and also serves as a central primary social space between the residents. However, this west-facing façade is exposed to intense afternoon sunlight, which has both benefits and challenges, as assessed in section 4.2.5: while it maximizes solar heat gain in winter, it creates a risk of overheating and visual discomfort through glare in summer.

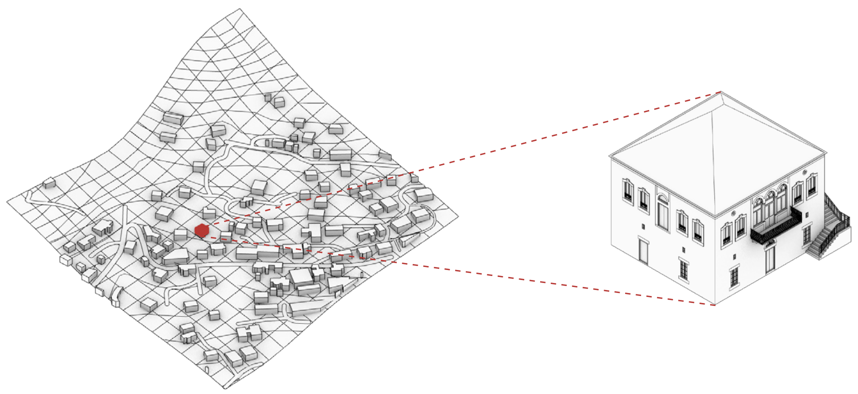


Figure 4.3.1.1 - Analyzed Central Hall House on site (Douma, Lebanon)

Source: Author's elaboration

Architectural elements such as high ceilings that are complemented with low windows and high circular openings (Taqat) promote the stack effect, and the triple-arched windows contribute significantly to the effective distribution of airflow - all potentially reducing indoor temperatures during the warm season.

Other ways that the house mitigates overheating through architectural features include green outdoor space with trees shading the facade, exterior shutters, and a deep positioning of the window in the wall. In some cases, a fountain or water point in the garden helps cool the air by evaporative cooling. Additionally, the thick sandstone

walls function as thermal mass, absorbing heat during the day and releasing it gradually at night, therefore regulating the indoor temperatures. The terracotta-tiles roof complements this effect, further buffering temperature fluctuations due to its high thermal inertia and ability to slow down heat flow into the house.

According to the local climate conditions analyzed using climate consultant 6.0, we have identified and selected the most effective passive strategies for heating and cooling applicable to our case study house (Table 4.3.1.1).

Table 4.3.1.1 – Selected Passive Cooling Strategies relevant to the case study house (selected from Table 2.3.3.2)

Source: Author's elaboration

Thermal Mass	Increase the thermal mass where needed
Solar Orientation & Apertures	Maximize winter sun exposure (and minimize summer heat)
	Triple-Arch window for potential winter solar gains

The westward orientation of traditional Lebanese houses exemplifies an adaptive architectural response to climatic conditions, balancing ventilation, daylighting, and thermal regulation.[107]

Building on this, the following section investigates how these passive strategies translate into actual indoor thermal comfort under unconditioned conditions, using both annual operative temperature data and adaptive comfort models to differentiate between cold stress in winter and heat stress in summer.

To assess comfort performance in the absence of mechanical systems and with the passive strategies, we analyze 2 key parameters:

1- Indoor Operative temperature (Dry Bulb and Mean Radiant Temperature MRT)

2- Prevailing Mean Outdoor Air Temperature

These parameters are essential to interpret indoor comfort conditions in accordance with ASHRAE 55 [108] and EN 15251 [109] standards for naturally ventilated buildings.

107 Yanjun Shen et al., "Damage Characteristics and Thermo-Physical Properties Changes of Limestone and Sandstone during Thermal Treatment from −30 °C to 1000 °C," Heat and Mass Transfer 54 (November 2018), https://doi.org/10.1007/s00231-018-2376-5.

108 ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), ANSI/ASHRAE Addendum d to ANSI/ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy, 55.

109 European Committee for Standardization (CEN), EN 15251:2007 – Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics (CEN – European Committee for Standardization, 2007).

Figure 4.3.1.2 compares the annual operative temperature of the Ground Floor (GF), the first floor (1st floor) and the roof. Operative temperature reflects both air temperature (Dry Bulb Temperature) and the radiant impact of surrounding surfaces (MRT), providing a representation of thermal comfort in passive buildings.

This figure indicates that the ground floor experiences lower and more stable temperatures year round, maintaining cooler conditions during both winter and summer. This internal stability is attributed to its thick masonry walls, shaped openings, and proximity to the earth which buffers against rapid outdoor fluctuations.

The first floor experiences greater thermal variation, with elevated operative temperatures during summer and lower comfort performance in winter.

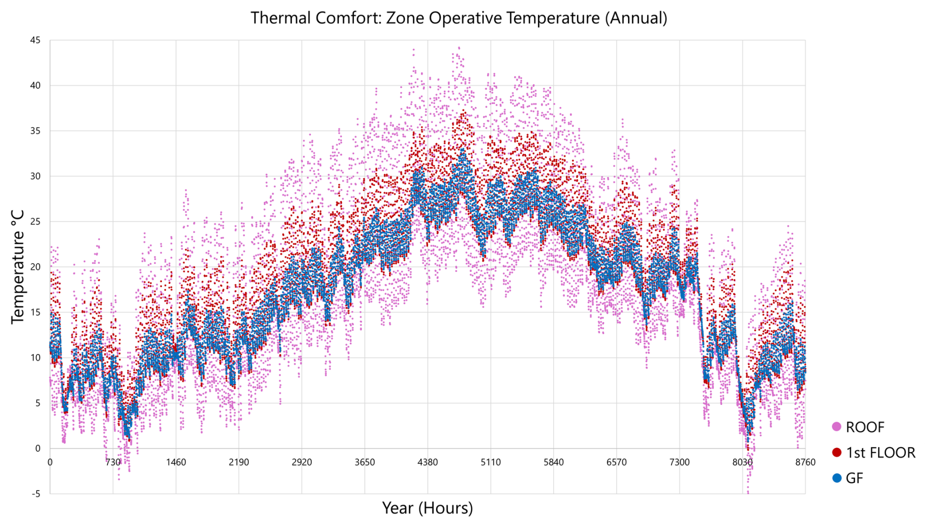


Figure 4.3.1.2 - Thermal Comfort Zone Operative Temperature (annual) – Comparison Graphs GF, 1st Floor and roof.

Source: Author's elaboration

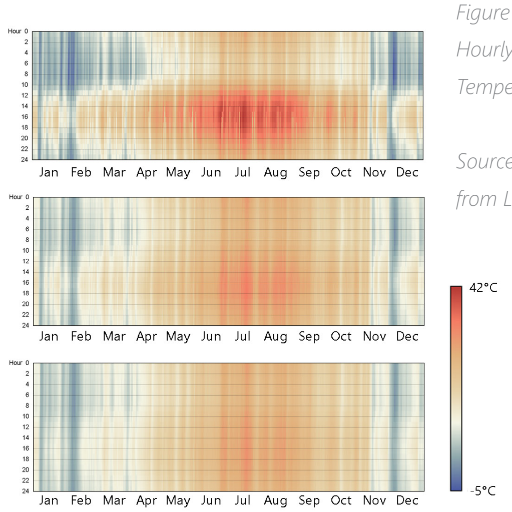


Figure 4.3.1.3 – Temperature Hourly Plot of Operative Temperature per Floors

Source: Author's elaboration from Ladybug, Grasshopper

The roof, though unoccupied and used solely for storage, displays the most temperature swings, indicating high exposure and limited thermal mass. These variations can result in heat transfer to the spaces below, especially in summer, which affects the thermal performance of the First Floor (Figure 4.3.1.2).

Those results are further illustrated in Figure 4.3.1.3, where the operative temperature hourly plot showcases the overheating and underheating present on each floor.

Adaptive comfort charts were generated for both the ground floor and the first floor (Figures 4.3.1.4 and 4.3.1.5). It helps determine how comfortable indoor temperatures feel to occupants depending on the outdoor temperature in naturally ventilated buildings.

The white diagonal band represents the comfort band and shifts diagonally because our comfort expectations change with seasons and outdoor temperature. [110]

As shown in the adaptive comfort charts (Figures 4.3.1.4 and 4.3.1.5), during the winter and shoulder seasons (January-April, October-December), a significant portion of data falls below the comfort band, indicating underheating, characterized by discomfort. This is illustrated in Figure 4.3.1.8 and 4.3.1.9 where it is labeled as "cold", an uncomfortable condition. This is in addition reinforced by looking at Figure 4.3.1.1 and 4.3.1.6 that shows that the average prevailing outdoor temperature falls below 18°C. This places these periods outside the typical adaptive comfort range, where occupants are more sensitive to cooler indoor conditions.

This is further supported by the operative temperature delta heatmap, where we observe a predominantly negative

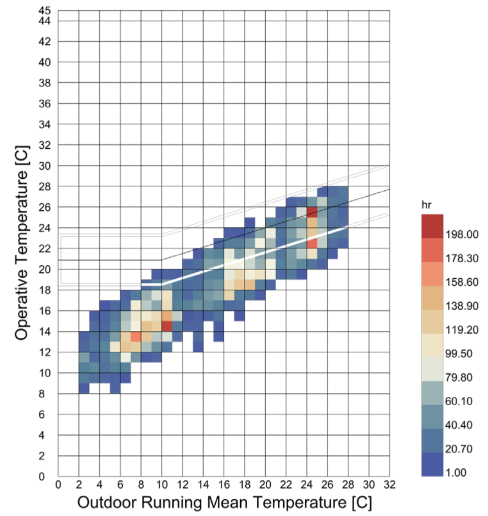


Figure 4.3.1.4 – Adaptive Comfort Chart on the Ground Floor

Source: Author's elaboration from Ladybug, Grasshopper

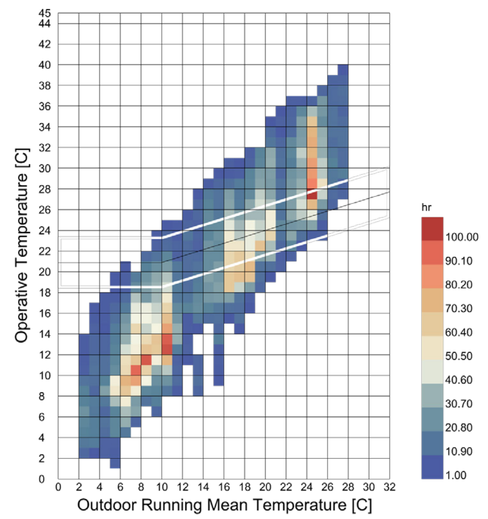


Figure 4.3.1.5 - Adaptive Comfort Chart on the First Floor

Source: Author's elaboration from Ladybug, Grasshopper

110 Olgyay, Design with Climate: Bioclimatic Approach to Architectural Regionalism.

temperature delta (ΔT) in figure 4.3.1.7 during these same months — indicated by darker blue shades. This suggests that the indoor operative temperature is lower than the outdoor temperature, especially during the early morning and late evening hours.

This thermal condition suggests that the building retains cold air or fails to capture enough passive heat, resulting in indoor environments that are uncomfortably cool for occupants during these months. The consistent misalignment with the adaptive comfort zone implies a potential need for passive solar heating strategies or improved thermal insulation to maintain comfort without active heating.

However, the ground floor's ability to maintain a cool and stable indoor environment proves beneficial during the summer months, where the operative temperature remains within the adaptive comfort zone, indicating little to no thermal discomfort. As seen in Figure 4.3.1.7 of the temperature delta (ΔT), we see a consistently negative or near-neutral delta during the hottest periods, suggesting that the indoor space stays cooler than outside, reducing the need for mechanical cooling. This is reinforced with Figure 4.3.1.9, showing the majority of the warm months as "neutral" according to the ASHRAE 55.[111]

111 ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), ANSI/ASHRAE Addendum d to ANSI/ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy.

Figure 4.3.1.6 – Prevailing Outdoor Temperature (C) Ground Floor

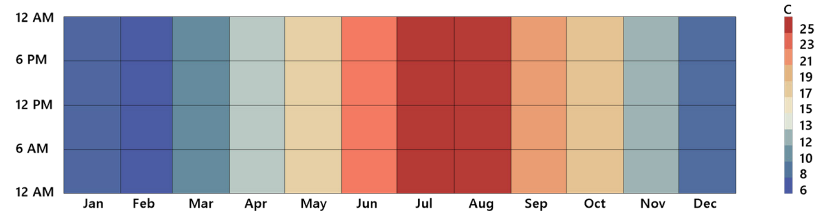


Figure 4.3.1.7 – Operative Temperature Delta (dC) Ground Floor

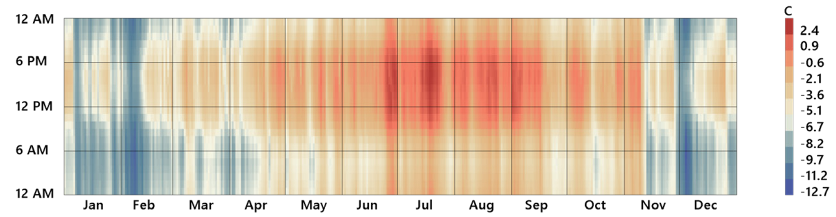


Figure 4.3.1.8 – Thermal Comfort Condition Ground Floor

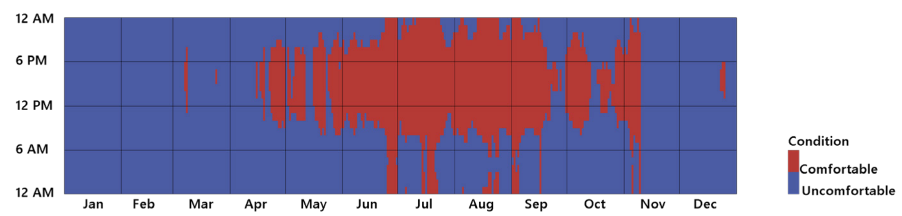
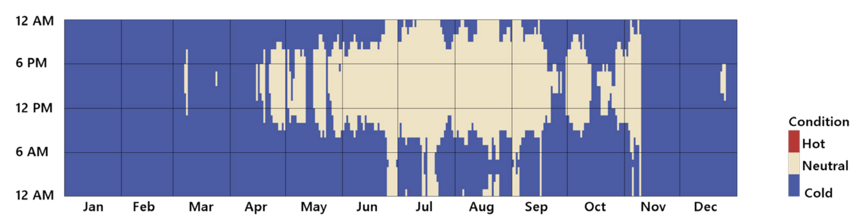


Figure 4.3.1.9 – Thermal Condition Ground Floor



In the case of the 1st Floor, fewer data points fall within the white comfort band, indicating a higher discomfort of 15.9% over the acceptable limit according to ASHRAE 55, compared to 8.2% on the ground floor. The primary issue on this level is seasonal overheating and underheating as seen in Figure 4.3.1.5, largely due to important temperature fluctuations (figure 4.3.1.1 and 4.3.1.2) throughout the year, making the first-floor occupants more susceptible to thermal discomfort.

The adaptive comfort chart shows that the data points lie above and below the upper threshold of the comfort zone (figure 4.3.1.5), especially as the outdoor temperature increases (figure 4.3.1.1). There is a visible clustering of the points outside the upper comfort limit, particularly above an outdoor temperature of 24°C and subsequently an indoor operative temperature (Figure 4.3.1.10). These conditions are likely due to increased solar gains, an absence of shading and limited thermal buffering on the first floor.

This tendency is confirmed by the operative temperature delta heatmap (ΔT) in figure 4.3.1.11, which shows strong red-orange bands across the summer months, especially from midday through late afternoon. This indicates that indoor temperatures are significantly higher than outdoor temperatures during these hours.

In contrast, during the colder months, the delta map shows mostly neutral, meaning the first floor is slightly warmer indoors than out, likely due to passive solar gains. However, this isn't enough to keep the space within the comfort zone, as figures 4.3.1.12 and 4.3.1.13 indicate a strong discomfort due to heat.

Interestingly, the delta heatmap also shows more extreme fluctuations across the day and year, reinforcing that the first-floor experiences greater thermal fluctuation, being cooler than the ground in winter and hotter in summer. This leads to lower thermal stability, affecting comfort negatively.

Figure 4.3.1.10 – Prevailing Outdoor Temperature (C) First Floor

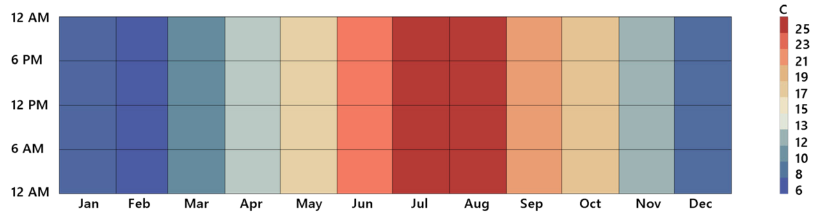


Figure 4.3.1.11 – Operative Temperature Delta (dC) First Floor

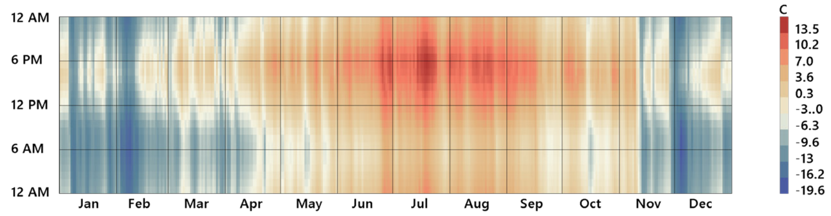


Figure 4.3.1.12 – Thermal Comfort Condition First Floor

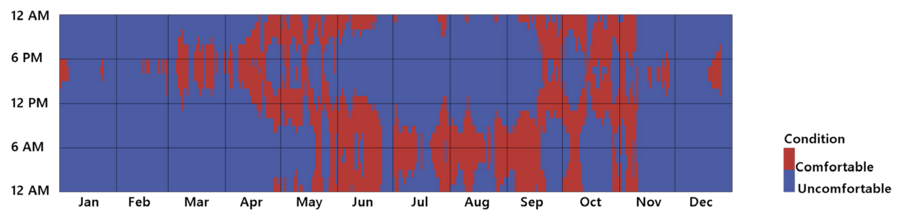
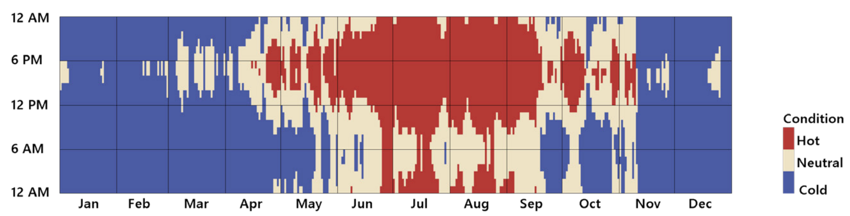


Figure 4.3.1.13 – Thermal Condition First Floor



4.3.2 DAYLIGHT ASSESSMENT AND DAYLIGHT FACTOR

Following the analysis of thermal comfort and passive heating and cooling strategies, it is essential to evaluate another key component of indoor environmental quality: daylight availability and visual comfort. Daylight plays a crucial role in enhancing the well-being of occupants and reducing the reliance on artificial lighting thus lowering the energy demands.

We will assess the daylight performance of the case study house using the Daylight Factor (DF) as defined by the EN 17037 standard, in reference to the comfort thresholds established in section 3.5.2. [112]

Since the case study is a traditional architecture, the dimensions and positions of openings are preserved to maintain the building's architectural integrity. Therefore, the daylight analysis focuses not on modifying window geometry but on assessing the existing daylight conditions and exploring potential improvements of glazing types and the use of the existing wooden louvered shutters as dynamic shading elements.

First of all, we can notice in Figure 4.3.2.1 that the ground floor experiences insufficient illuminance across all orientations, with the highest daylight factor (> 3.1%) concentrated only near the windows, particularly in rooms 11 and 16. These localized red peaks are possibly indicating potential glare, in contrast with the interior zones of all rooms who are well below the 1.23% DF threshold (Table 3.5.2.1), indicating poor daylight availability in the core spaces, are represented in blue on the simulation plan.

According to the EN 17037, our target level is 2% of the outdoor daylight level for at least 50% of the space.

This target was calculated in section 3.4.2 using Douma's average global horizontal illuminance (Table 3.4.2.1). However, Figure 4.3.2.1 shows that the ground clearly fails to meet this threshold, indicating a strong dependence on artificial lighting for visual comfort throughout the year.

Due to the absence of openings on the south side, this orientation does not contribute to the floor's natural lighting. Additionally, the thick walls further restrict light penetration, worsening the low illuminance levels throughout the space, as illustrated in table 4.3.2.1 which presents the daylight factors per room. This spatial layout is consistent with traditional Lebanese architecture, where window placement and room depth lead to uneven daylight

112 "EN 17037 Daylight Provision - ClimateStudio Latest Documentation."

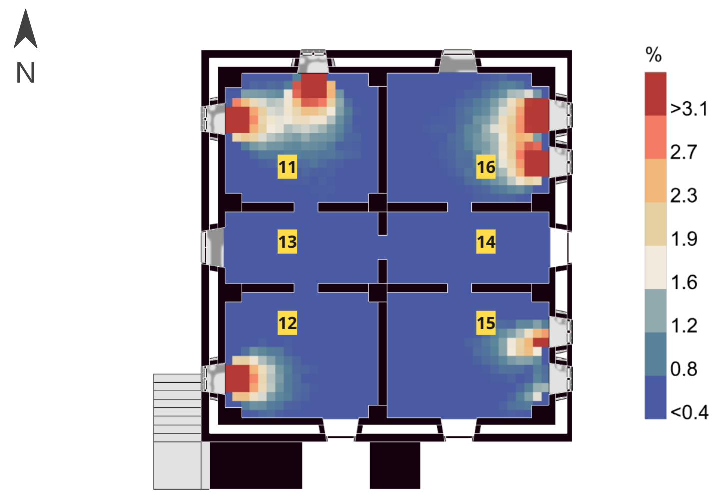


Figure 4.3.2.1 – Daylight Factor on the Ground Floor

Table 4.3.2.1 – Daylight Factor Results per Room on the Ground Floor

DISPLAY NAME	FLOOR	ORIENTATION	DF
12	GF	SW	0.50
11	GF	NW	0.96
16	GF	NE	0.97
15	GF	SE	0.99
13	GF	W	0.03
14	GF	E	0.03

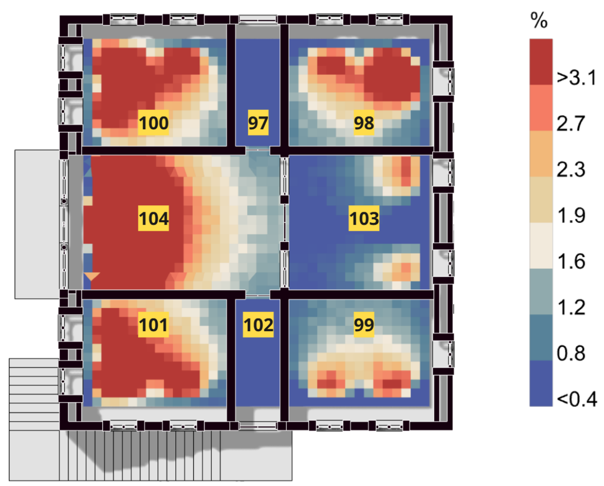


Figure 4.3.2.2 – Daylight Factor Results per Room on the First Floor

Table 4.3.2.2 – Daylight Factor Results per Room on the First Floor

DISPLAY NAME	FLOOR	ORIENTATION	DF
98	1st Floor	NE	1.89
97	1st Floor	Corr N	0.04
100	1st Floor	NW	2.42
99	1st Floor	SE	1.90
102	1st Floor	Corr S	0.04
101	1st Floor	SW	2.45
104	1st Floor	W	3.25
103	1st Floor	E	0.91

distribution, reflecting the original use of this floor as a storage space or animal stables.

Unlike the ground floor, the first floor benefits from a better natural light quality but faces a major issue with high daylight factors peaking around the windows (< 3.1%) and uneven light distribution within spaces (Figure 4.3.2.2). For example, room 103 which has very low DF away from the windows, and normal DF at the base of the windows because the east is a beneficial sun orientation in summer and winter.

The primary factor contributing to the high DF values is the triple arch and the windows on the west, which allows significant sunlight penetration at a medium to low solar angle, and as seen in Figure 4.2.5.6 of Section 4.2.5, the north-western sun orientation is particularly harmful during the warm months, leading to overheating and potential glare. In addition, Table 4.2.5.4 indicates that the WNW orientation is harmful at a high angle. However, Figure 4.2.5.3 indicates that the west-southern orientation remains beneficial during the winter months, contributing to solar heat gains when they are most needed.

Building on the daylight analysis which revealed that the ground floor does not experience issues with excess light, our focus will be on optimizing daylight control on the first floor using existing vernacular strategies.

The triple arch, a defining architectural feature, typically lacks exterior shutters. Meanwhile, the traditional exterior shutters operate in two distinct modes. Fully open when the shutters are secured in place using shutter holdbacks after being manually opened, or fully closed and locked using shutter latches, bolts, or espagnolette locks to ensure security and light control (Figure 4.3.2.3). Therefore, to test their effectiveness in reducing excessive sunlight, we will simulate the condition where these shutters are completely closed in the most affected rooms, and specifically on the side where the daylight factor is the highest.

For the ground floor, where the daylight factor is already limited, we will address daylight optimization in a later phase through targeted interventions. At this stage, our objective is to fully explore and assess the performance of existing vernacular strategies in regulating indoor daylight quality before introducing additional modifications.

Figure 4.3.2.3 - Exterior Shutters

Source: Author's elaboration

Daylight Assessment and Daylight Factor

Following the identification of excessive daylight exposure and glare in the southeast and southwest rooms, we tested the impact of fully closed exterior shutters on the daylight factor (DF) in these spaces. According to EN 17037, our DF target is 2.06% for at least 50% of the time, with an acceptable range between 1.23% and 3.09% (threshold values in Section 3.5.2, Table 3.5.2.1).

With fully closed shutters on the west and east orientations only, results in table 4.3.2.3 show that the daylight factor in the affected rooms 98, 99, 100 and 101 all dropped to the minimum threshold of 1.23-1.24% but indicated a significant reduction in overall availability.

When fully closing the shutters exclusively on the south openings, daylight performance also deteriorated in some cases. For example, the results in table 4.3.2.4 show that room 99 dropped well below the minimum DF target, while room 101 dropped to the minimum threshold similarly to the previous cases.

In conclusion, the results indicate that shutters offer the most adaptable and passive solution, when operated with consideration for glare comfort.

Furthermore, if equipped with a locking mechanism that allows them to be fixed at specific angles, shutters could significantly improve the daylight performance for all spaces.

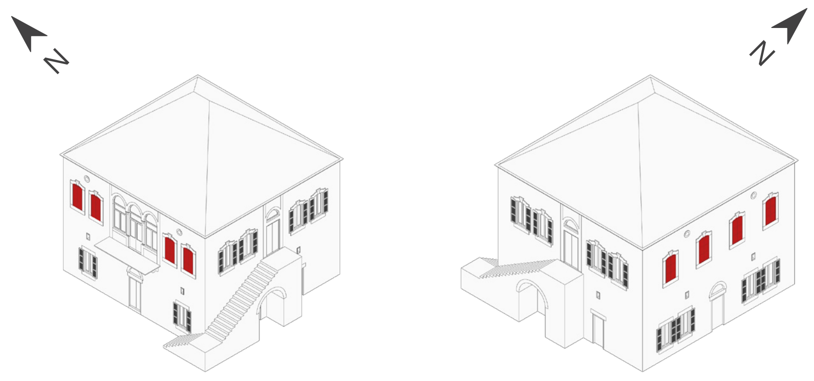


Figure 4.3.2.3 – East and West Shutters Completely Closed

Table 4.3.2.3 - Results of Daylight Factor for Fully Closed East and West Shutters

DISPLAY NAME	FLOOR	ORIENTATION	NEW DF *EW shutters*	*Previous DF*
98	1st Floor	NE	1.24	1.89
97	1st Floor	Corr N		0.04
100	1st Floor	NW	1.24	2.42
99	1st Floor	SE	1.24	1.90
102	1st Floor	Corr S		0.04
101	1st Floor	SW	1.23	2.45
104	1st Floor	W		3.25
103	1st Floor	E		0.91

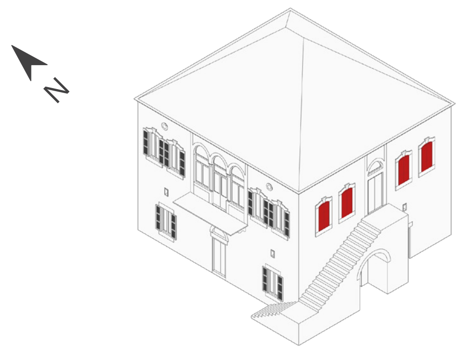


Figure 4.3.2.4 – South Shutters Completely Closed

Table 4.3.2.4 - Results of Daylight Factor for Fully Closed South Shutters

DISPLAY NAME	FLOOR	ORIENTATION	NEW DF *S shutters*	*Previous DF*
98	1st Floor	NE		1.89
97	1st Floor	Corr N		0.04
100	1st Floor	NW		2.42
99	1st Floor	SE	1.67	1.90
102	1st Floor	Corr S		0.04
101	1st Floor	SW	1.23	2.45
104	1st Floor	W		3.25
103	1st Floor	E		0.91

4.4 CASE N - THE CONVENTIONAL HOUSE (SEMI-REFURBISHED)

The following section continues from Case A preserving the same thermal properties of the envelope (Table 4.4.1), while including active heating systems.

It represents a semi-refurbished home equipped with **active heating**, with **additional loads** such as:

- **Heating System** (using biomass as fuel)
- **Lighting** (electricity as fuel)
- **Equipment** (electricity as fuel)

ROOF	U-val	2.49
NS EXT WALL *1st Floor*	U-val	2.72
EW EXT WALL *1st Floor*	U-val	0.97
EXT WALL *GF*	U-val	0.98
PARTITION	U-val	1.11
INTERMEDIATE SLAB	U-val	2.21
ATTIC FLOOR	U-val	1.54
GF SLAB	U-val	2.79
WINDOWS	U-val	5.89
	G-val	0.91

Table 4.4.1 – Summary of Thermal Performance of Envelope Elements (reproduced from table 4.2.3.2)

Source: Author's elaboration

4.4.1 HEATING SYSTEMS AND OPERATIONAL SETTINGS

In section 4.2.1, we determined that usually, the ground floor (GF) of a traditional Lebanese house is used as storage and remains unheated, relying on the thermal mass on the stone walls. As it remains significantly cooler than the first floor, it was typically used as a summer room.

Case N represents a semi-refurbished structure with a heating system installed on both the ground floor and the first floor. This follows the results of the survey conducted in section 3.4.4, highlighting that the majority of the owners who refurbish a traditional Lebanese house repurpose the ground floor as a living quarter.

As for the heating system, it consists of a traditional wood-fueled sobia positioned in the central living room. The radiant heat warms up the surrounding rooms, but in the simulation, it is modeled as an **Ideal Air Load (IAL)** system, using the measured stove's efficiency and primary energy factor.

The internal loads of Case N are defined as follows:

Occupants:

- According to section 4.2.2, we consider that our household has **4 occupants.**

With a floor area of 184.13 m2, and a total house area of 420.26 m2 (184.13 x 2) we get:

- People Density = $\frac{Occupants}{Floor\ Area\ m^2}$

- **People Density** = $\frac{4}{420.26}$ = **0.01**

- We set the people density of the house as **0.01** (4 occupants) which is considered **low density**.

Metabolic rate (MET):

- Metabolic Equivalent of Task (MET) = **1.1**

This value is according to both ASHRAE 55 [113] and EN 16798-1 [114], who allow flexibility. These standards define 1.0 MET for seated/resting (living rooms, bedrooms), 1.2 MET for light activity (kitchens, circulation zones). Therefore, we will use 1.1 MET for a conservative average for a whole-house comfort analysis.

113 ASHRAE, ASHRAE Handbook - Fundamentals.

114 European Committee for Standardization (CEN), EN 16798-1:2019 – Energy Performance of Buildings — Ventilation for Buildings — Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics — Module M1-6 (CEN – European Committee for Standardization, 2019).

Lights Power Density (PD):

The value used in the simulation is based on the ASHRAE 90.2[115], and on the CIBSE TM39 that states that:

"Older lighting systems using incandescent or halogen technologies typically result in lighting power densities of 10–15 W/m²." [116]

- Lighting PD = **12 W/m²** for a target of **500 lux.**

Air Change Rate:

We set an ACH = 2 [118] since it is an old leaky house.

Natural Ventilation:

We set the following parameters, so that the windows are considered open only if those exterior conditions are met:

Nat Vent Set Point = 23°C
Min Out Air Temp = 17°C
Max Out Air Temp = 30°C
Max Out RH = 80%

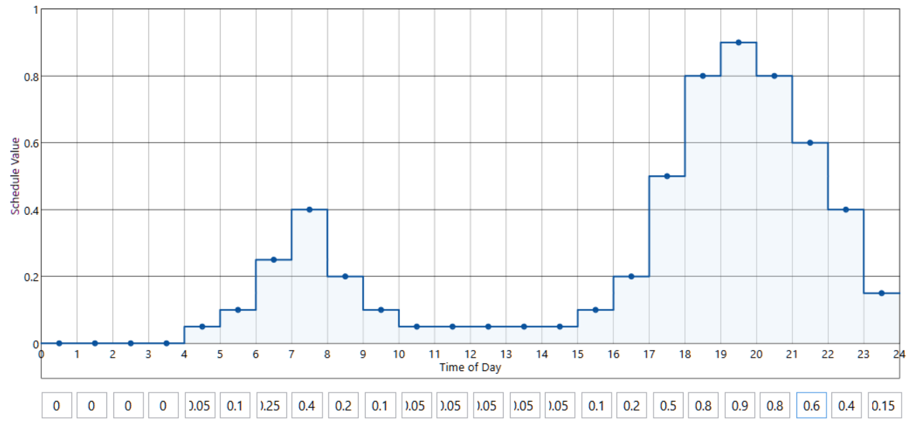


Figure 4.4.1.1 - Lighting Schedule used in the Simulation

Source: Author's elaboration from Climate Studio, Grasshopper

Lighting schedule:

The lights are on for approximately 6h/day, however sometimes lights are partly on (e.g., 0.25 = quarter load), sometimes fully on (0.9 in evening), but overall, it averages out to 6 h/day at full LPD (Figure 4.4.1.1).

Equipment Power Density (PD):

- Equipment PD[117] = **2 W/m²**

Natural Ventilation Schedule:

The schedule is set during the overheating period, to provide passive cooling, from 16th April to 31st October, with a gradual reduction (Figure 4.4.1.2 and 4.4.1.3).

Heating Schedule:

The heating schedule is set for the underheating period determined in Section 4.1.2 (Figure 4.1.2.4), from 1st November to 15th April, with an operable area of 0.7 (Figure 4.4.1.4 and 4.4.1.5).

115 ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), ANSI/ASHRAE/IES Standard 90.2-2018: Energy-Efficient Design of Low-Rise Residential Buildings. Table B-1

116 Chartered Institution of Building Services Engineers, TM39: Energy Use in Buildings: Energy Benchmarking (CIBSE, 2009), https://www.cibse.org/knowledge-research/knowledge-portal/tm39-building-energy-metering.

117 ASHRAE, ASHRAE Handbook - Fundamentals, Chapter 18, 2017.

118 Alberto Jiménez Tiberio and Pablo Branchi, "A Study of Air Leakage in Residential Buildings," paper presented at 2013 International Conference on SmartMILE (SmartMILE), IEEE, 2013, https://doi.org/10.1109/SmartMILE.2013.6708180.

Heating Systems and Operational Settings

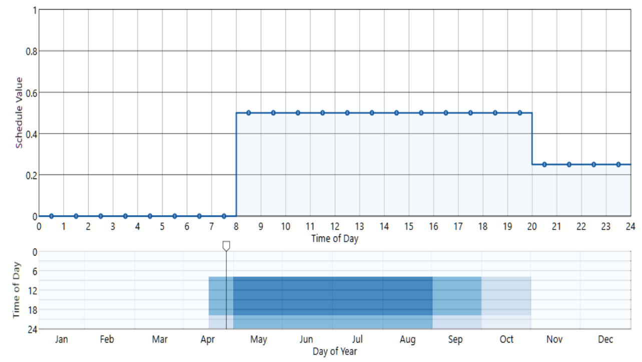


Figure 4.4.1.2 - Natural Ventilation Schedule used in the Simulation - Shoulder Seasons

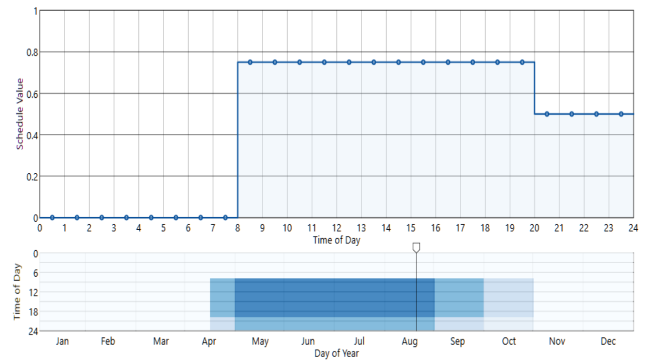


Figure 4.4.1.3 - Natural Ventilation Schedule used in the Simulation - Summer

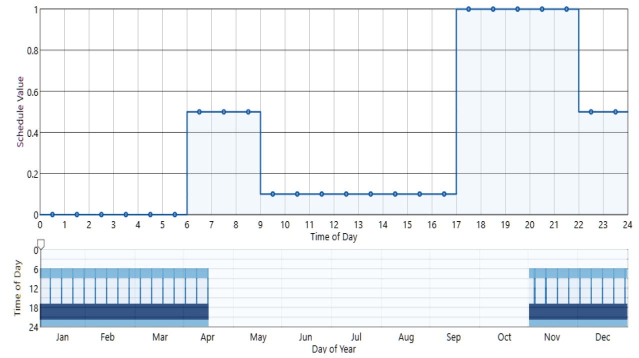


Figure 4.4.1.4 - Heating Schedule used in the Simulation - Weekdays

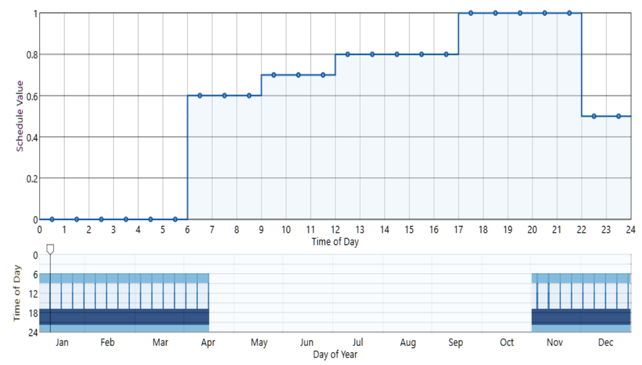


Figure 4.4.1.5 - Heating Schedule used in the Simulation - Weekends

Source: Author's elaboration from Climate Studio, Grasshopper

4.4.2 FUEL TYPES, SYSTEM EFFICIENCY, PRIMARY ENERGY FACTORS

The heating system in Case N uses wood as its primary fuel source. The Primary Energy Factor (PEF) is 1 since wood is considered a renewable source (section 2.3.1).

According to Table 2.3.3.1 in Section 2.3.3 (Existing Heating and Cooling Practices), the efficiency of a traditional wood-fueled sobia is 54% ($\eta = 0.54$).[119] Those wood-fired traditional sobia embody the most commonly used heating systems in the regions that require space heating. As seen in section 2.3.2, in 2023, 41% of households with access to a heating source used wood, followed by a less popular use of diesel, whose use dropped between 2022 and 2023. [120]

However, despite its popularity, wood as a heating fuel in Lebanon has several drawbacks. Due to the political instability of the country, fuelwood supply is largely unregulated and sometimes sourced illegally, playing a part in deforestation. In addition, as smoke exhaust pipes are often not adapted to traditional Lebanese houses, potential smoke leakage indoors could happen. This results in elevated indoor air pollution levels, which may have harmful health effects on its inhabitants (survey in Section 3.4.4).

On the other hand, wood-fueled heating systems have potential for improvement. More efficient and newer types of stoves are available on the market today and can achieve 75-80% efficiency (table 2.3.3.1), offering both environmental and health benefits if adopted. [121]

119 Jensen et al., Field Study of Energy Performance of Wood-Burning Stoves.

120 United Nations High Commissioner for Refugees (UNHCR) et al., VASyR 2023 – Vulnerability Assessment of Syrian Refugees in Lebanon: Thematic Energy Report.

121 Jensen et al., Field Study of Energy Performance of Wood-Burning Stoves.

4.4.3 DELIVERED AND PRIMARY ENERGY CALCULATION METHODOLOGY

After inputting the heating system along with its efficiency, fuel type, and respective Primary Energy Factor (PEF), we proceed to evaluate the results from the energy simulations. First, we extract and process the raw outputs which are the energy needs. They help us assess the building's thermal performance and effectiveness, independently of the system efficiency. The delivered energy (DE) indicates the actual energy input required from the heating

system to meet those needs, accounting for losses due to system inefficiency. Finally, the primary energy (PE) reflects the total upstream energy demand, helping us to compare the environmental impact of different fuel sources.

We obtain the energy demand in joules E(J) directly from the Grasshopper energy simulation. To convert this value into useful energy demand in kilowatt-hours (kWh), we divide it by 3,600,000:

$$\text{Useful Energy Demand (kWh)} = \frac{E\ (J)}{3{,}600{,}000}$$

Next, we calculate the Delivered Energy (DE) by dividing the useful energy demand by the efficiency of the heating system, as given in section 4.4.2, based on table 2.3.3.1. In this case, the system is a traditional sobia stove.

$$DE = \frac{\textit{Useful Energy Demand}}{\textit{Efficiency}}$$

$$DE = \frac{(PE\ (kWh/m^2) \times Area\ m^2)}{\textit{Efficiency}}$$

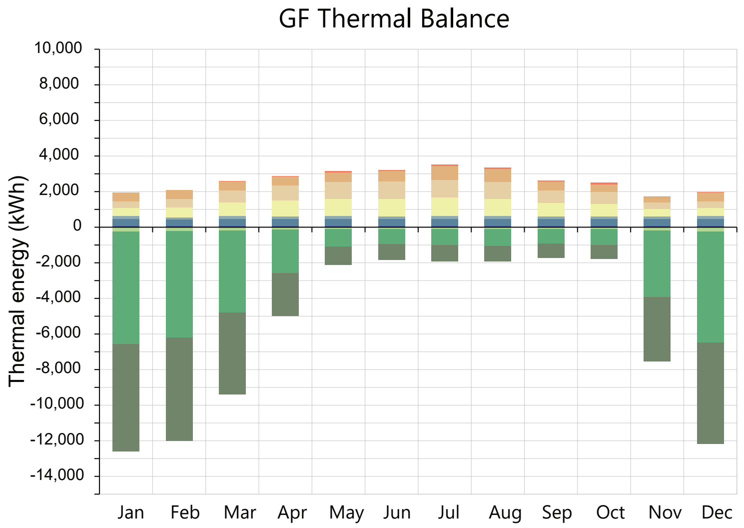
Finally, we determine the Primary Energy (PE) by multiplying the delivered energy by the primary energy factor (PEF) of the fuel used. Since the fuel is wood, the PEF is 1.0, according to section 4.4.2, based on table 2.3.3.1.

$$PE = \frac{\left(\frac{\textit{Useful Energy Demand}}{\textit{Efficiency}}\right) \times PEF}{Area\ m^2}$$

$$PE = \frac{(DE \times PEF)}{Area\ m^2}$$

4.4.4 ENERGY DEMAND AND CARBON FOOTPRINT

After simulating the model of Case N, we obtain the following results:



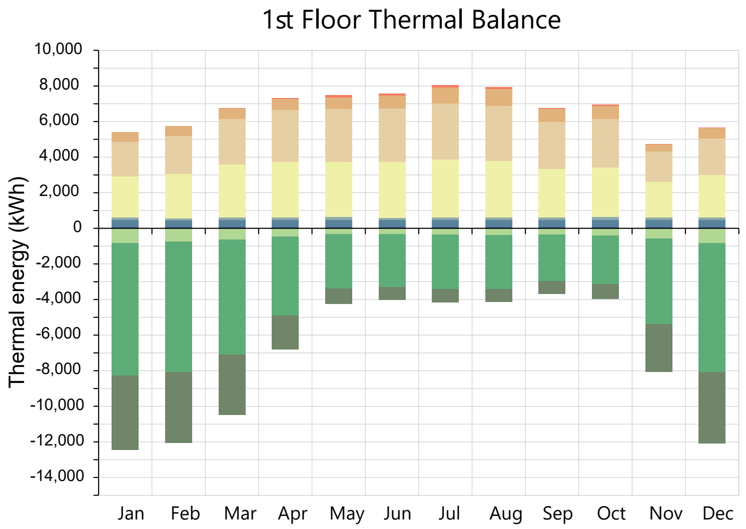
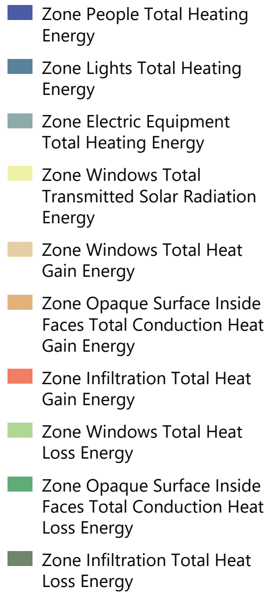


Figure 4.4.4.1 - Thermal Balance of the GF of Case N

Figure 4.4.4.2 - Thermal Balance of the 1st Floor of Case N

Source: Author's elaboration from Climate Studio, Grasshopper



The **thermal balance** is carried out to understand what causes heat losses and gains through both the building's opaque and transparent envelope, and internal sources, helping us account for all the energy entering and leaving the system. It helps us assess energy demand and comfort conditions.

Mostly heat loss from the opaque surfaces and infiltration (likely due to the ACH = 2, see section 4.4.1). Slight heat gains from the windows, and the opaque surfaces.

Just like the GF, this floor experiences mostly heat loss from the opaque surfaces and infiltration (likely due to the ACH = 2, see section 4.4.1), but in addition experiences major heat gains from the windows, and the opaque surfaces.

Thermal Energy Needs:

This is translated into the thermal energy needs of the system, which is the theoretical amount of heating or cooling energy required by the building to maintain comfort conditions indoors, assuming ideal systems (no losses, perfect efficiency). This then shows us the intrinsic performance of the structure.

Since the analysis focuses only on heating needs to address thermal discomfort during the winter period, the results reveal a significantly high demand for heating in the cold months. The results indicate strong heat losses and a strong need for heating to reach thermal comfort.

Figure 4.4.4.3 - Thermal Energy Needs of the GF

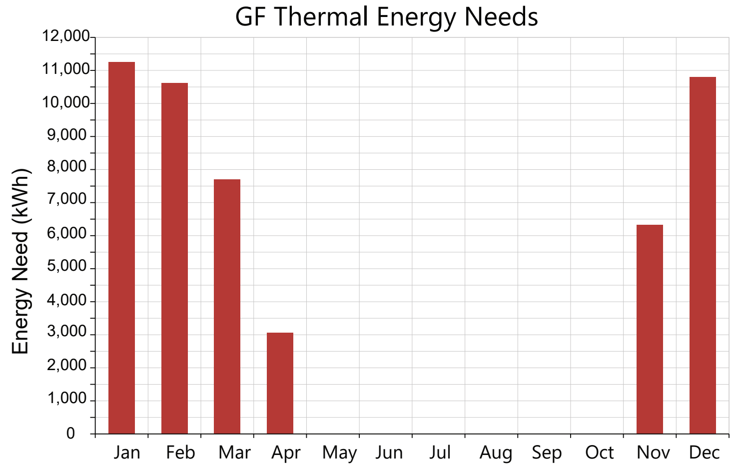
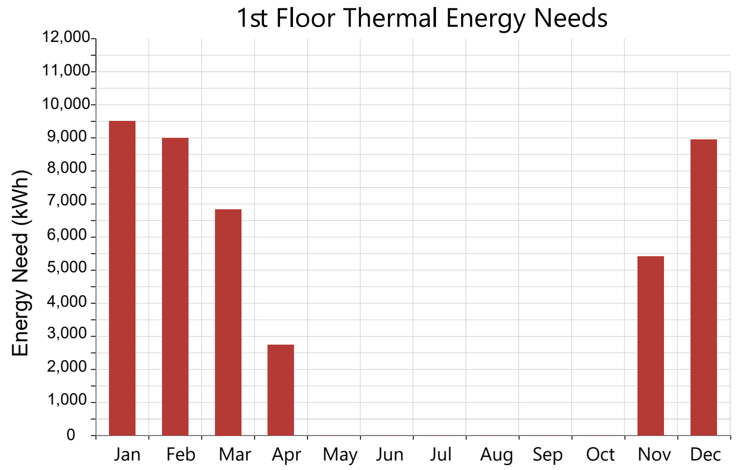
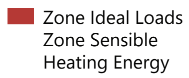


Figure 4.4.4.4 - Thermal Energy Needs of the 1st Floor

Source: Author's elaboration from Climate Studio, Grasshopper





Delivered Energy:

Next, these thermal energy needs are translated into delivered energy which is the actual amount of energy that must be supplied to the building by systems (boiler, heat pump, electricity, wood, etc.). Thus value takes into account the respective system efficiencies (η, COP, SCOP) as well as distribution and storage losses.

Figures 4.4.4.5 and 4.4.4.6 highlight the high heating consumption, which can be attributed both to the low system efficiency (54%) and to the large volume of space that must be heated in order to maintain the thermal comfort threshold of 21 °C.

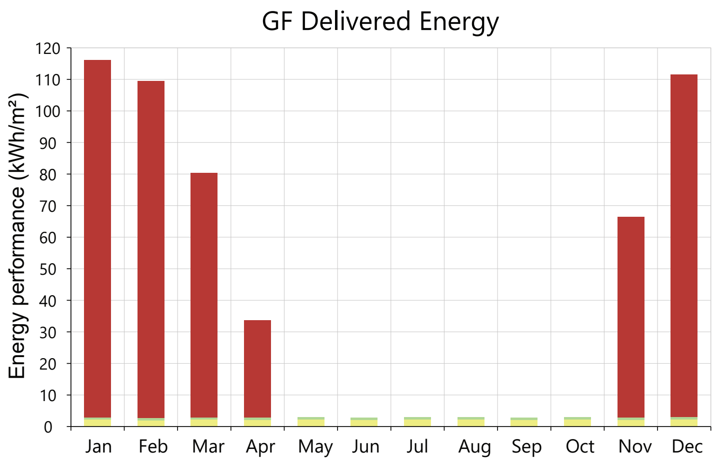


Figure 4.4.4.5 - Delivered Energy of the GF

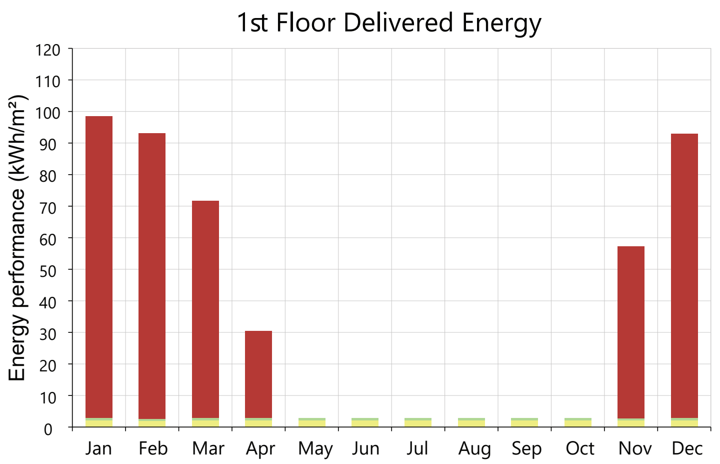


Figure 4.4.4.6 - Delivered Energy of the 1st Floor

Source: Author's elaboration from Climate Studio, Grasshopper

EP Lighting
EP Equipment
EP Heating

Primary Energy Uses:

Finally, delivered energy is converted into primary energy by applying the primary energy factor (PEF). It is the upstream energy that accounts for all extraction, transportation and production of natural sources that are used to produce this energy, and takes into account any conversion, generation and distribution losses. This last indicator provides a comprehensive measure of the building's overall energy demand and impact on natural resources.

The results shown in Figures 4.4.4.7 and 4.4.4.8 show that the primary energy consumption is significantly influenced both by the choice of energy carrier and by the efficiency of the systems used. In case N, the PEF equals 1 due to wood being a renewable source (section 4.4.2), the results align with the thermal energy needs and delivered energy.

Figure 4.4.4.7 - Primary Energy Uses of the GF

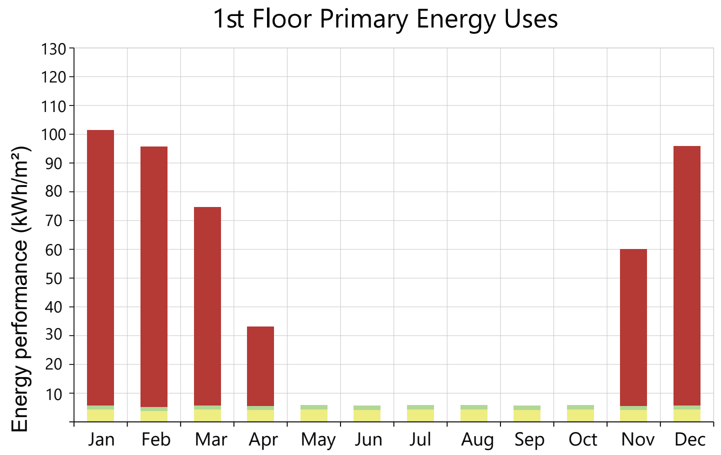
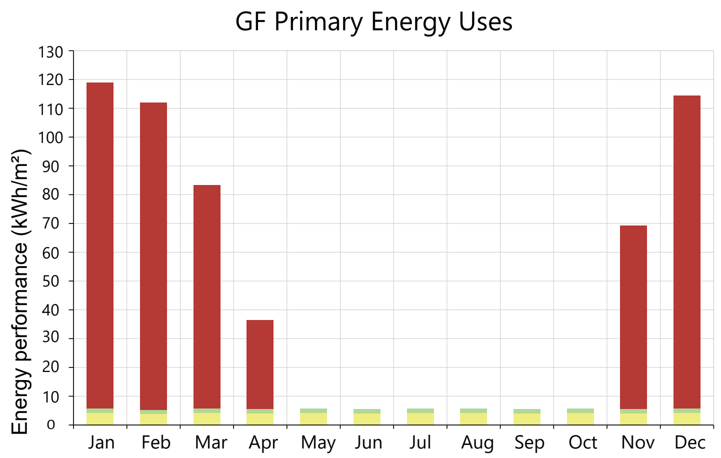


Figure 4.4.4.8 - Primary Energy Uses of the 1st Floor

Source: Author's elaboration from Climate Studio, Grasshopper

EP Lighting
EP Equipment
EP Heating



4.4.5 COMFORT ANALYSIS

In order to determine the thermal comfort inside the house, we measure the zone operative temperature to understand how the temperature fluctuates per floor, including the roof, since the common attic floor can influence the indoor climate of the 1st floor. Since the roof is not thermoregulated, we notice some significant temperature fluctuations between the winter and summer months. However, unlike Case A (Section 4.3.1, Figure 4.3.1.1) we can observe that the use of mechanical heating improves the operative temperature of both the ground floor and the 1st floor.

Although, similarly to Case A, the ground floor still shows more stable temperature fluctuations throughout both the winter and summer months, maintaining a more moderate indoor climate compared to other spaces,

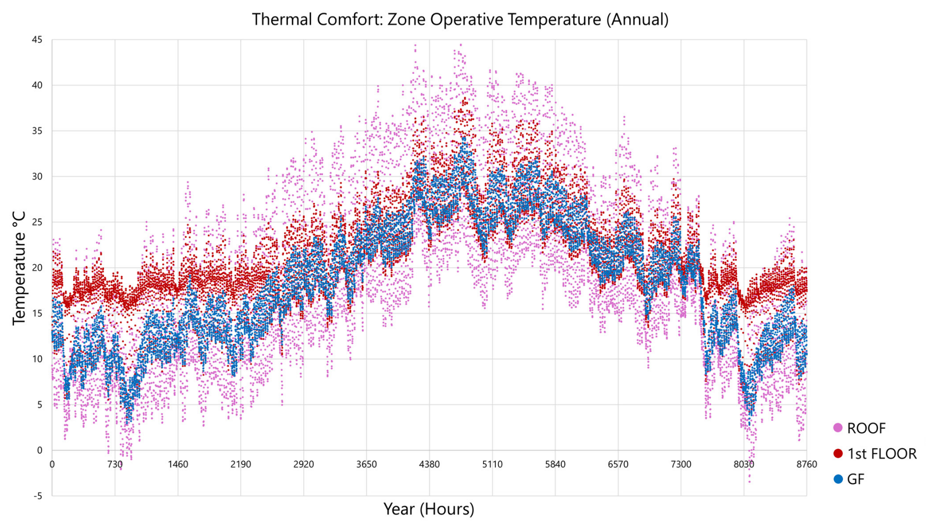


Figure 4.4.5.1 - Thermal Comfort - Annual Zone Operative Temperature of the whole House

Source: Author's elaboration

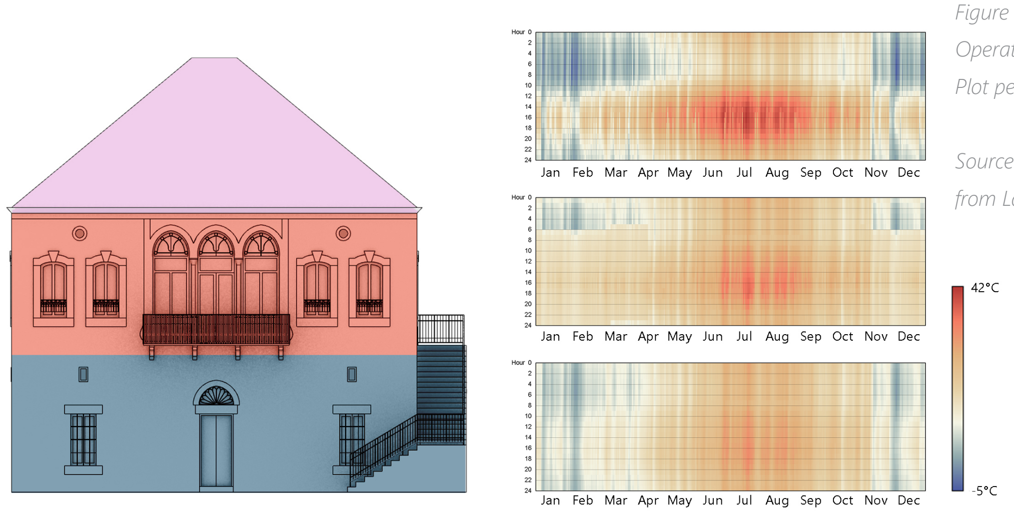


Figure 4.4.5.2 - Comparative Operative Temperature Hourly Plot per Floors

Source: Author's elaboration from Ladybug, Grasshopper

and therefore seeing a major improvement in the thermal comfort (Figure 4.4.5.1). This reinforces the finding in section 4.4.4 (Figures 4.4.4.1 and 4.4.4.2) that one of the main problems for heat loss and gain is the envelope, indicating a need for its refurbishment.

In order to assess thermal comfort, we use the PMV model for a conditioned (heated) space. This model quantifies the air temperature (Dry Bulb Temperature), the Mean Radiant Temperature (MRT), the Relative Humidity (RH), the Air Velocity, the Metabolic Rate (MET) and the Clothing Insulation (Clo). [122]

The PMV output ranges between -3 (cold) to +3 (hot), where 0 represents thermal neutrality, also known as comfort, which provides a quantitative measure of the occupants' thermal sensation. In parallel, the PPD (Predicted Percentage Dissatisfied) expresses the share of occupants dissatisfied with the thermal conditions, linking directly to the PMV values obtained. These are summarized in the two other figures of thermal comfort condition and discomfort reason.

In Figure 4.4.5.3, we can observe that on the ground floor (GF), the PMV ranges between -1 and -2 (slightly cool to cool) during most of the winter daytime, while at night between 0:00 and 6:00 it often drops to -3 (cold). In summer, this floor remains comfortable for the majority of the time, with occasional values of -2 (cool) during some nights in the shoulder season.

However, in Figure 4.4.5.7, we can notice that the 1st floor show a higher sensitivity to outdoor temperature. The PMV shows sensations of cool to cold during winter days, particularly at night, while in summer the values exceed the comfort threshold, reaching +1 (slightly warm) for most of the day, and rising as high as +3 (hot) during peak sun hours.

This potentially highlights the impact of the uninsulated roof and envelope on the 1st floor indoor climate. This difference can be further illustrated by the simulated indoor heat stress, which amounts to **9.2%** on the GF compared to **13.9%** on the 1st floor over the year.

122 ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), ANSI/ASHRAE Addendum d to ANSI/ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy, 55.

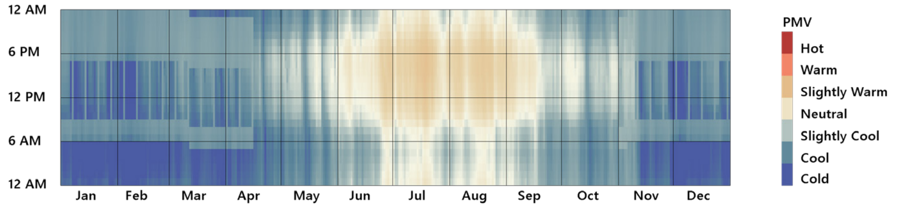


Figure 4.4.5.3 - Predicted Mean Vote (PMV) on the GF

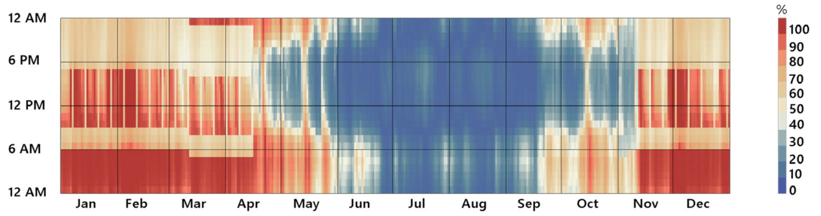


Figure 4.4.5.4 - Predicted Percentage Dissatisfied (PPD) on the GF

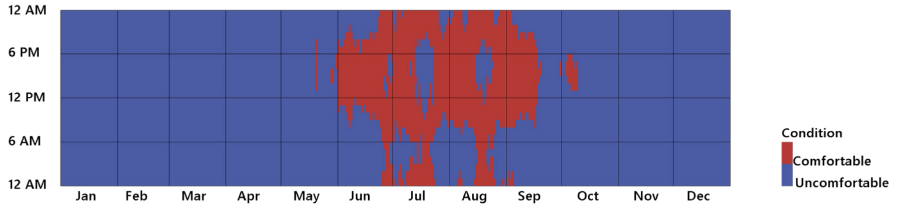


Figure 4.4.5.5 - Thermal Comfort Condition on the GF

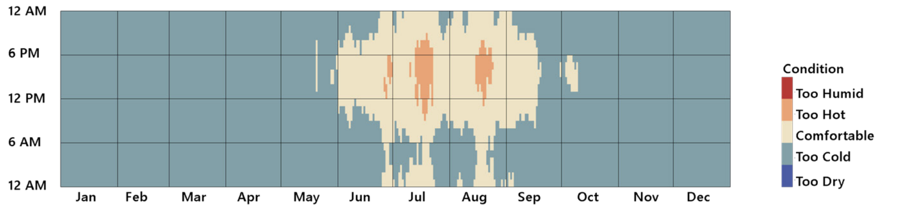


Figure 4.4.5.6 - Discomfort Reason on the GF

Source: Author's elaboration from Ladybug, Grasshopper

Comfort Analysis

Figure 4.4.5.7 - Predicted Mean Vote (PMV) on the 1st Floor

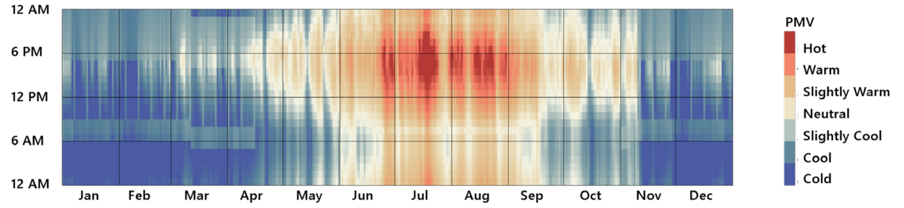


Figure 4.4.5.8 - Predicted Percentage Dissatisfied (PPD) on the 1st Floor

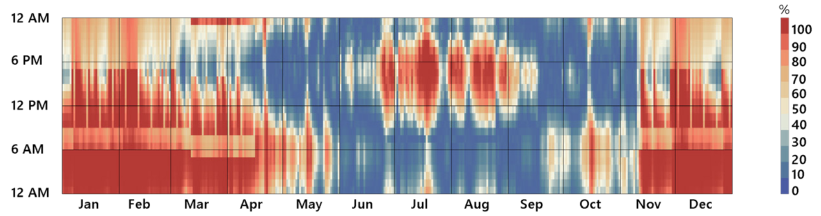


Figure 4.4.5.9 - Thermal Comfort Condition on the 1st Floor

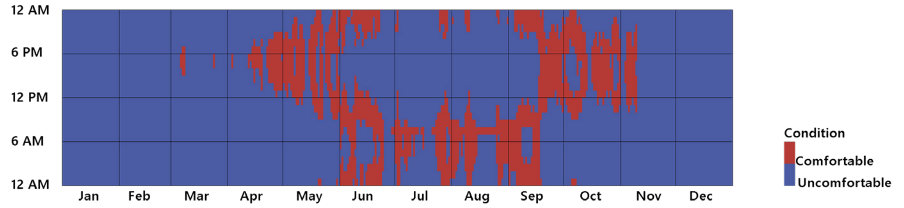
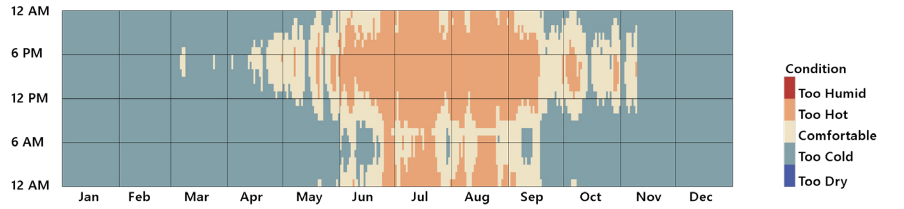


Figure 4.4.5.10 - Discomfort Reason on the 1st Floor

Source: Author's elaboration from Ladybug, Grasshopper



4.5 CASE S - REGULATED HOUSE (STANDARD)

This following section aims to understand if the building guidelines proposed by the Order of the Engineers in Lebanon through the TSBL can be potentially used as a guideline for the traditional Lebanese house retrofitting, and if it helps with improving comfort and energy performance of the existing structure.

4.5.1 APPLICATION OF STANDARD U-VALUES

According to the TSBL guidelines, a retrofit plan was compiled to modify each envelope element in order to match the prescribed thermal properties. For each element, the corresponding materials used to achieve those values were specified, along with their respective impact on the house (Table 4.5.1.1).

Case S therefore follows the same heating operational settings and internal loads as Case N but differs through the application of the hypothetical U-values defined in the TSBL (Section 2.2.1), in order to evaluate potential improvements in energy efficiency and thermal comfort.

Just like Case N, we still have too much heat loss from the opaque surfaces and infiltration (likely due to the ACH = 2, see section 4.4.1).

Reduction in heat gains from the windows, and the opaque surface 1st floor heat gains are still slightly higher than the GF

ELEMENT	Case A/N U-value	Case S U-value	MODIFICATION	IMPACT
ROOF	2.49	0.63	Wood fiber insulating boards 80mm	Low
WALL *GF*	0.98	0.77	Hemp-lime plaster 35mm (interior)	Low
WALLS *1st Floor*	1.82	0.77	Wood fiber insulating board 30mm Hemp-lime plaster 35mm	Moderate
GF SLAB	2.70	0.77	Mineral Wool 40mm	Moderate
WINDOWS	5.89 SHGC 0.91	3.80 SHGC 0.39	Low-E Single Glazing U-val 3.80 SHGC 0 0.39 Tvis = 0.90	Moderate

Table 4.5.1.1 - Standard Case Material Description

Source: Author's elaboration

4.5.2 ENERGY DEMAND AND CARBON FOOTPRINT

After simulating Case S, we obtained the following results in the thermal balance: the first floor shows overall lower heat gains and losses compared to Case N (Figure 4.4.4.2) yet still experiences major losses through infiltration and conduction across the envelope. The ground shows the same behavior but at a proportionally lower magnitude, while also retaining important losses from infiltration and envelope conduction.

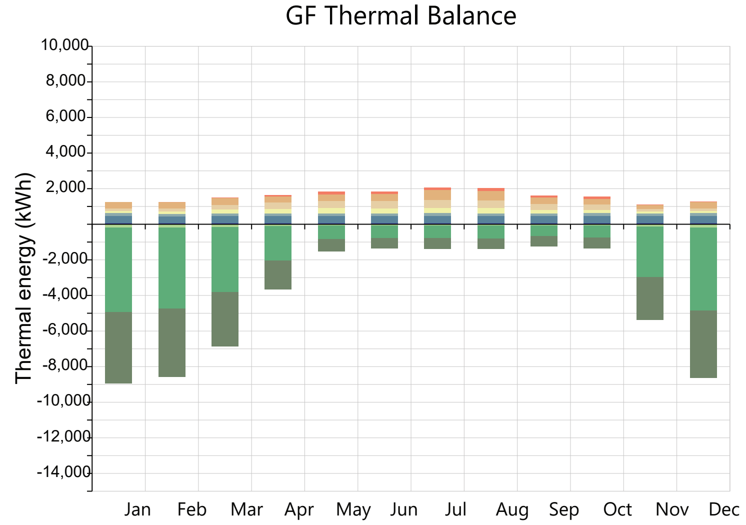


Figure 4.5.2.1 - Thermal Balance of the GF of Case S

Source: Author's elaboration from Climate Studio, Grasshopper

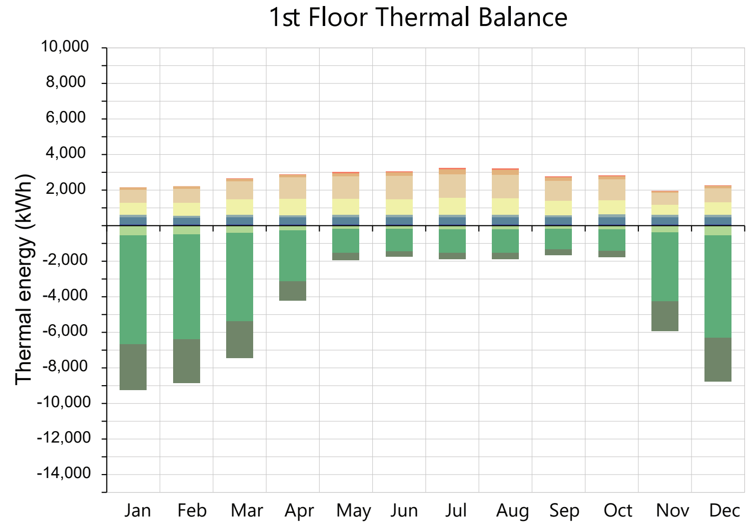
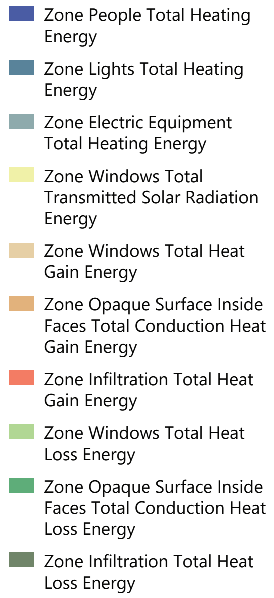


Figure 4.5.2.2 - Thermal Balance of the 1st Floor of Case S



1 Thermal Energy Needs

We observe a reduction in the overall thermal needs compared to Case N (Figures 4.4.4.3 and 4.4.4.4). For example, in January the demand decreases from about 11,000 kWh in Case N to around 8,000 kWh in Case S.

Since the walls are now equally insulated with a U-value of 0.77 (Table 4.5.1.1), the system reaches a more balanced state between heat gains and losses, resulting in consistently lower thermal energy needs.

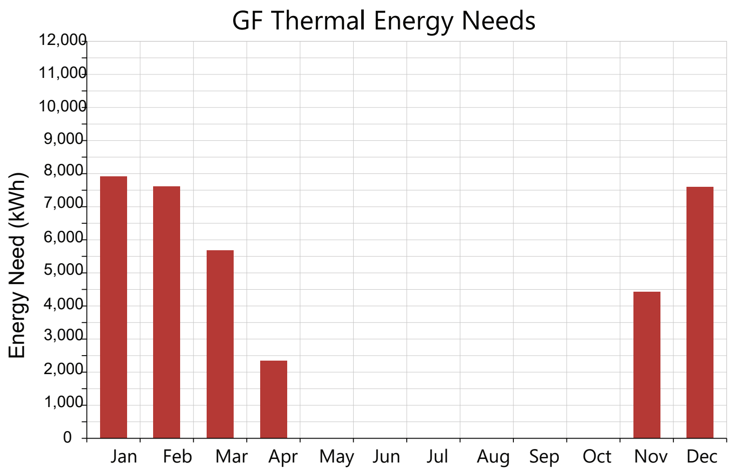


Figure 4.5.2.3 - Thermal Energy Needs of the GF

Source: Author's elaboration from Climate Studio, Grasshopper

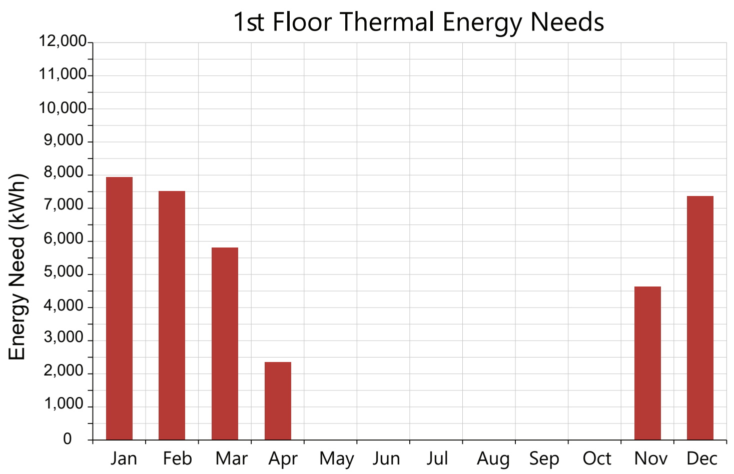


Figure 4.5.2.4 - Thermal Energy Needs of the 1st Floor

Source: Author's elaboration from Climate Studio, Grasshopper

2 Delivered Energy

Since the heating system is the same as Case N, the efficiency is still 54% and the Primary Energy Factor (PEF) equals 1, as wood is still used as fuel, making the heating consumption still too high.

The delivered heating uses are still proportional to the thermal needs, as shown in figures 4.5.2.5 and 4.5.2.6. Thermal hot stress is reduced from 9.2% to **8.7%** on the ground floor, and from 13.9% to **12.1%** on the first floor, a notable improvement compared to Case N.

This highlights the different heating dynamics of the two floors: while the first floor has slightly higher delivered energy due to its greater exposure through the roof and facades, the ground floor has some thermal buffering from its contact with the ground, which results in lower operative temperatures and proportionally higher heating requirements to reach the thermal comfort.

Figure 4.5.2.5 - Delivered Energy of the GF

Source: Author's elaboration from Climate Studio, Grasshopper

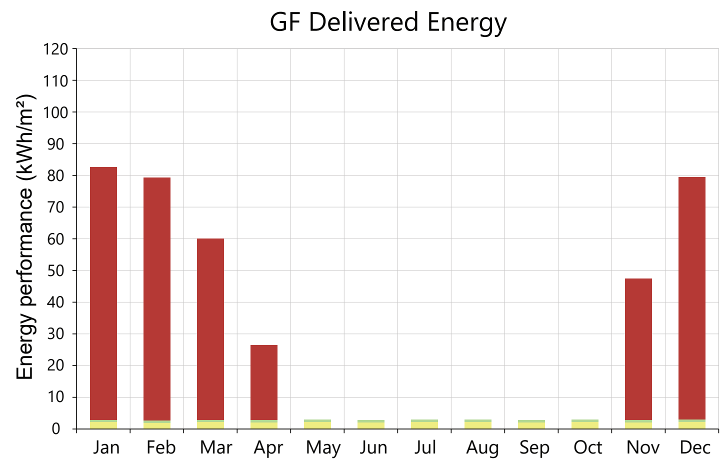
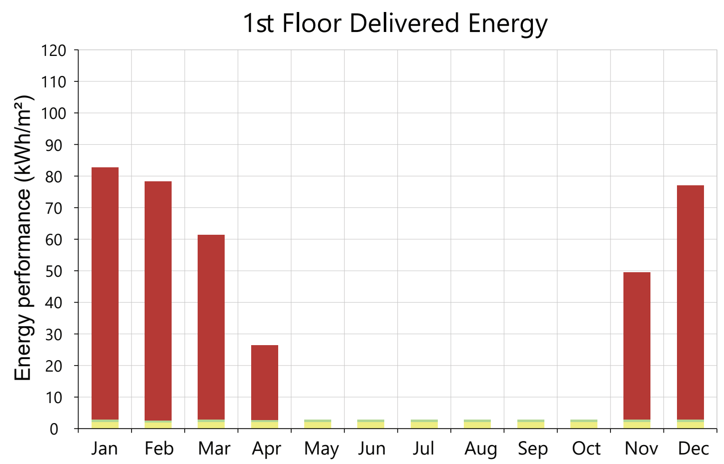


Figure 4.5.2.6 - Delivered Energy of the 1st Floor

Source: Author's elaboration from Climate Studio, Grasshopper



3 Primary Energy Use

As mentioned before, to convert the delivered energy into primary energy we use the primary energy factor (PEF) equals to 1.

Since the energy carrier and the efficiency of the system remain unchanged but the overall envelope is more performant, the results seen in Figures 4.5.2.7 and 4.5.2.8 align with the thermal energy needs (Figure 4.5.2.3 and 4.5.2.4) and delivered energy (4.5.2.5 and 4.5.2.6).

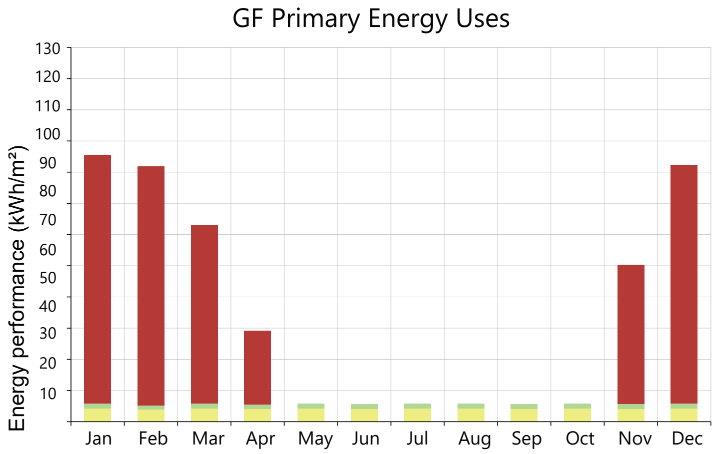


Figure 4.5.2.7 - Primary Energy Uses of the GF

Source: Author's elaboration from Climate Studio, Grasshopper

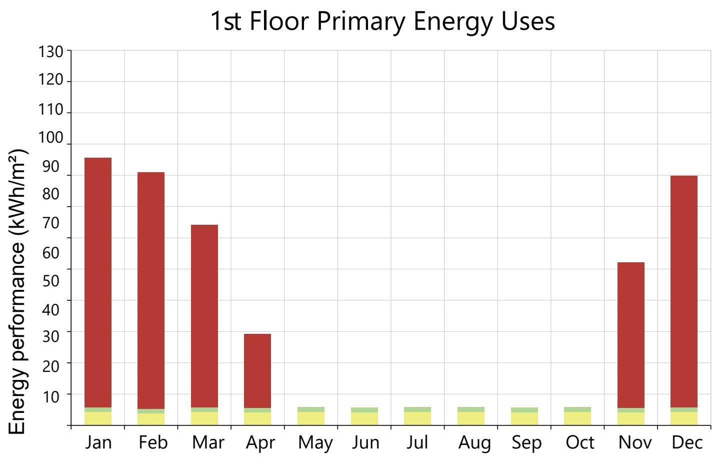


Figure 4.5.2.8 - Primary Energy Uses of the 1st Floor

Source: Author's elaboration from Climate Studio, Grasshopper

4.5.3 COMFORT ANALYSIS

In order to determine the thermal comfort inside the house, we measure the zone operative temperature of each floor including the roof. Both Case N and Case S still show the same overall temperature dynamics of cold winters and hot summers with the roof being the most exposed. However, in winter we can notice a modest improvement in Case S with slightly higher temperatures in all floors (around 2-3°C). In summer, the overheating roof is slightly dampened (from above 40°C to around 37-40°C), which indirectly affects the 1st floor. This is seen in the drop of thermal heat stress from 9.2% (Case N) to **8.7%** (Case S) on the ground floor, and 13.9% (Case N) to **12.1%** (Case S) on the 1st floor.

Figure 4.5.3.1 - Thermal Comfort - Annual Zone Operative Temperature of the whole House (Case S)

Source: Author's elaboration

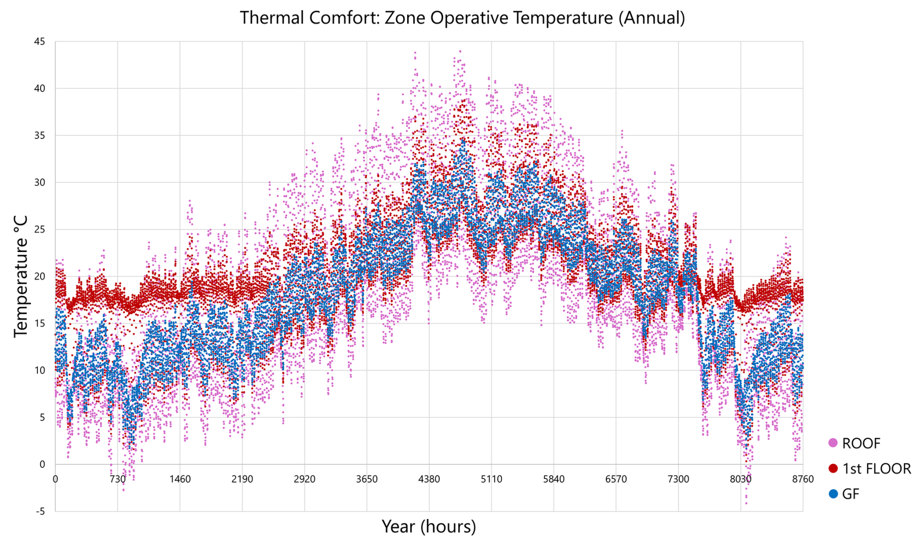
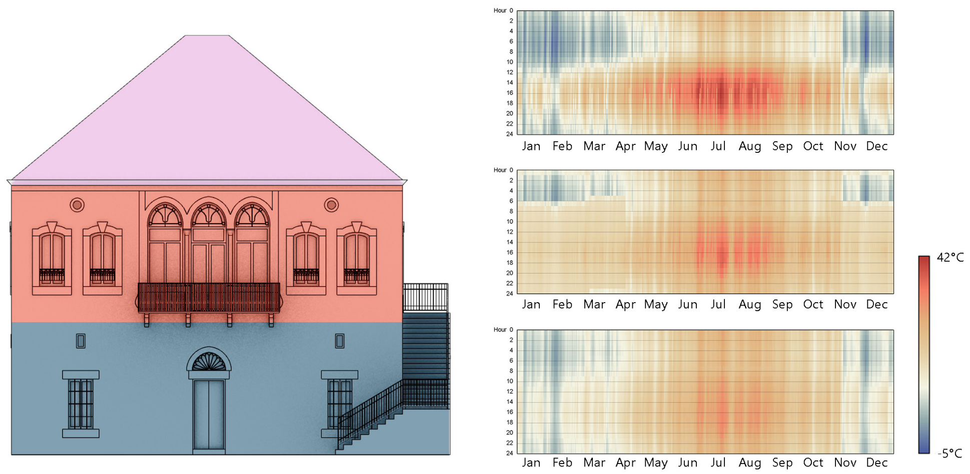


Figure 4.5.3.2 - Comparative Operative Temperature Hourly Plot per Floors

Source: Author's elaboration from Ladybug, Grasshopper



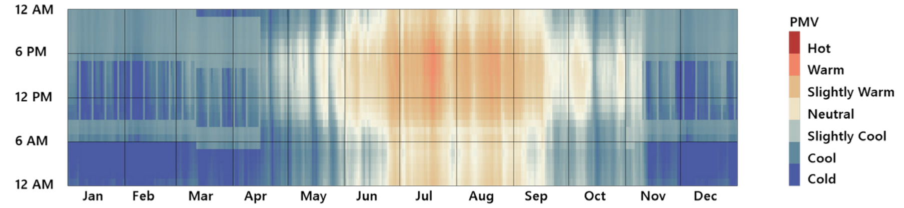


Figure 4.5.3.3 - Predicted Mean Vote (PMV) on the GF

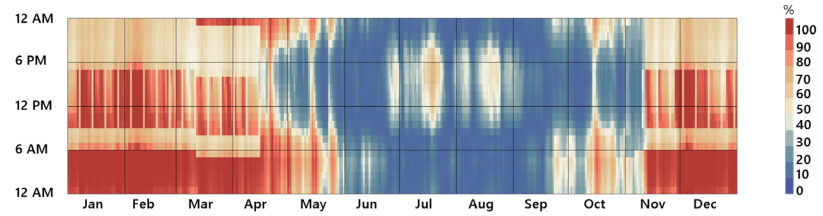


Figure 4.5.3.4 - Predicted Percentage Dissatisfied (PPD) on the GF

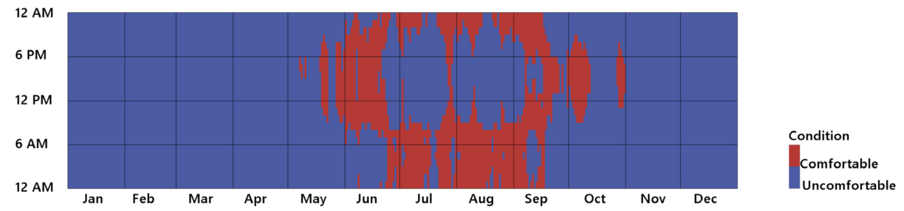


Figure 4.5.3.5 - Thermal Comfort Condition on the GF

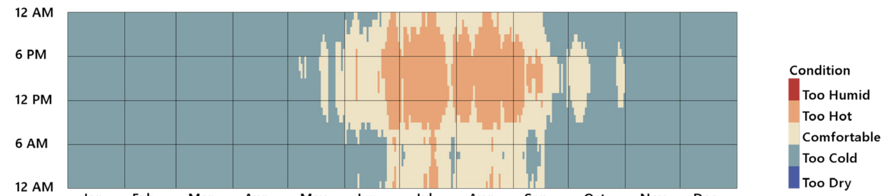


Figure 4.5.3.6 - Discomfort Reason on the GF

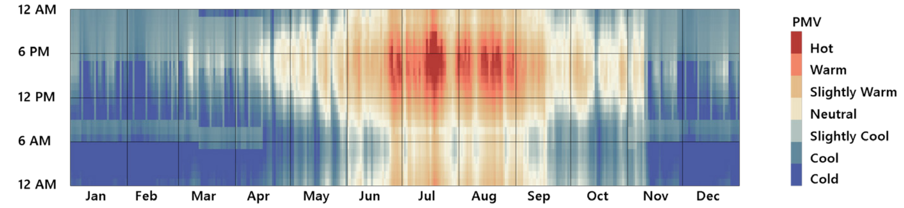


Figure 4.5.3.7 - Predicted Mean Vote (PMV) on the 1st Floor

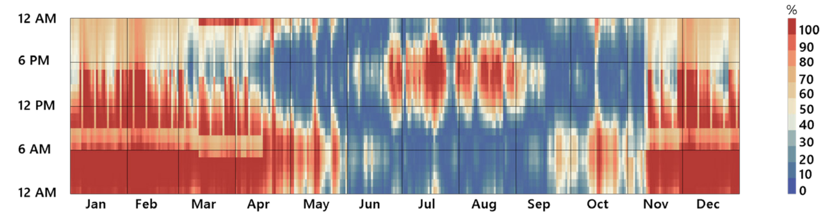


Figure 4.5.3.8 - Predicted Percentage Dissatisfied (PPD) on the 1st Floo

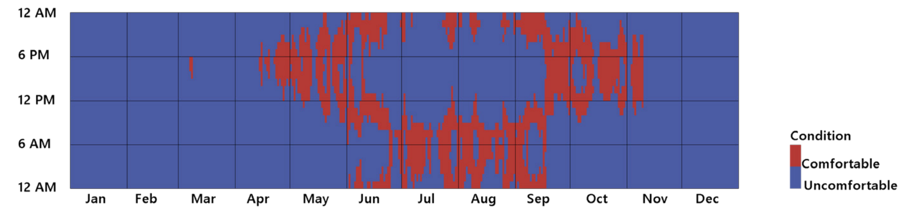


Figure 4.5.3.9 - Thermal Comfort Condition on the 1st Floor

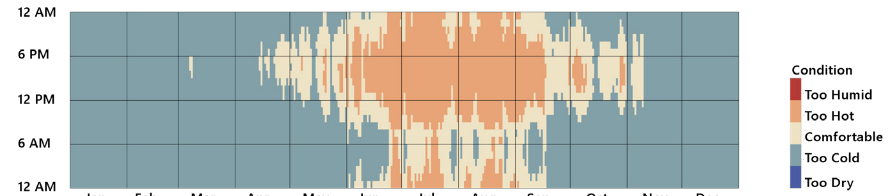


Figure 4.5.3.10 - Discomfort Reason on the 1st Floor

Case N has more scattered points across the graph, unlike Case S which has slightly smoother clusters proving the retrofit works to buffer the house from outdoor swings, but not dramatically. This is mostly due to the fact that the TSBL guideline for retrofitting applies to regulation level U-values and G-values but does not intervene on the active systems or deep retrofit measures. Therefore, this improves performance moderately but doesn't change the thermal profile.

In conclusion, refurbishing the envelope and equally draft proofing it restricts the heat loss and gains and improves comfort, but not dramatically.

Both Case N and S show a similar thermal profile because the retrofit targeted the envelope and not the active heating system or solar exposure.

In Case S, the floors are slightly warmer in winter compared to Case N, due to the added insulation on the external envelope and reduced infiltration rate (ACH 2 to ACH 1.3) which cuts heat losses.

The roof still overheats in summer but less than in Case N because of the improved roof insulation and some solar gains, reducing the overheating in the house.

Importantly, since the heating system remains inefficient (η = 54%, PEF = 1 for wood), the delivered heating energy is still high due to its exposure through the roof and the facades, while the ground floor benefits from soil buffering but still records thermal stress in winter.

4.5.4 SUMMARY AND CONCLUSION: COMPARISON CASE A - N - S

Moving from Case A (Adaptive passive house) to Case N (semi-refurbished with active heating and internal loads), we notice how crucial it is to introduce active systems in traditional Lebanese houses.

Thermal comfort:

In Case A, without heating or internal loads, the house remains strongly dependent on its passive features. The GF shows relatively stable and cooler temperature year-round compared to the 1st floor, likely due to its contact with the ground that provides thermal buffered. The 1st floor is very exposed to the elements through its numerous windows on the facades and contact with the roof, and experiences strong seasonal fluctuations. Comfort hours remain low, highlighting severe underheating in winter and overheating on the 1st floor in summer.

In Case N, the installation of a wood-fueled stove sobia improves operative temperatures in winter, reducing the extent of cold discomfort. The PMV values are closer to neutral during the day on the GF, while the 1st floor, although slightly better in winter, continues to suffer from overheating in summer. Annual stress amounts to 6.7% on the GF and 12.4% on the 1st floor.

This is all translated through the energy performance of the house. CaseA, being fully passive, has no primary or delivered energy demand. However, in Case N, the heating demand is very high due to the strong envelope losses through infiltration (ACH = 2) which is typical for non-refurbished old stone houses. The delivered energy is high due to the traditional stove's low efficiency (η = 54%), while primary energy remains equivalent to delivered energy due to the PEF being 1 for wood. The final demand is excessive for such a system and can be explained by the single system trying to heat up a very large volume for each floor. Lighting and equipment add modest contributions to the loads compared to heating.

From this comparison, we can notice that introducing heating systems improves winter comfort considerably, especially on the GF, but comes at the expense of a very high demand of energy if the system isn't adequate and efficient.

Moving from Case N (baseline with heating) to Case S (TSBL guideline retrofit) shows the effect of applying regulation-level envelope upgrades while keeping the same active system.

Case N retains the same temperature profile, with scattered operative temperatures that reflect the building's weak envelope. Thermal stress is high: 9.2% on the ground floor and 13.9% on the 1st floor. However, Case S demonstrates modest but measurable improvements: the operative temperature in winter rises by 2-3°C, and the roof overheating is slightly reduced (peaks fall from >40 °C to 37–40 °C). This indirectly lowers the overheating on the 1st floor and the ground floor. The thermal heat stress improves to 8.7% on the GF and 12.1% on the 1st floor, and we can notice a difference in the scattered plots who are now smoother clusters, indicating a more buffered response to outdoor swings.

In the case of energy performance, Case N exhibits very high heating demand due to the envelope and infiltration losses. Case S has the same heating system and setup, but the infiltration rate is reduced from 2 to 1.3 which leads to a significant drop in heating demands (e.g., January heating demand drops from ~11,000 kWh to ~8,000 kWh). The delivered energy decreases in proportion, but since the heating system remains inefficient, the overall heating consumption is still too high. The floor dynamics in energy persist: the 1st floor shows slightly higher delivered heating use due to its exposure through facades and roof, while the GF benefits from its ground buffering, but still requires proportionally more heating to offset low temperatures.

Case S achieves moderate gains in energy efficiency and comfort, reducing thermal stress and heating needs compared to Case N, which shows that relying on the envelope's passive strategies has an important impact. However, because the retrofit is only targeting the envelope and not the active system or shading, the overall thermal profile remains similar, which will lead us to target both the passive and active strategies of the house to achieve proper energy performance and thermal comfort.

This step-by-step comparison between Case A, Case N, and Case S highlights the gradual improvements and limitations of conventional retrofit approaches. It moreover shows that the combination of regulatory envelope improvements and addition of an active heating system result in moderate overall performance and comfort. This next chapter investigates a range of both passive and active strategies, assessing their impact on the energy use and occupant comfort. This will result in a sensitivity analysis per floor that helps us identify the most effective solutions and establish retrofit packages with different levels of impact on the house.

Table 4.5.4.1 - Summarized Comparison of Case and Results of Cases A - N - S

Source: Author's elaboration

	CASE A	**CASE N**	**CASE S**
ENVELOPE	Mixed wall thickness Mixed U-values	Same as Case A	Samewall thickness Same U-values
LOADS	No internal loads No heating	GF: Lighting 1st Floor: Lighting + Heating	Same as Case N
HEATING PE AND DE	-	Heating PE = DE = 463.7 kWh/m²/y	Heating PE = DE = 443.1 kWh/m²/y
DISCOMFORT (HOT STRESS) *Adaptive*	GF: 8.2% 1st F: 15.9%	GF: 9.2% 1st F: 13.9%	GF: 8.7% 1st F: 12.1%

Summary and Conclusion: Comparison Case A-N-S

05 RETROFITTING & OPTIMIZATION

Retrofitting Strategies

5.1 RETROFITTING STRATEGIES

The following table is a comprehensive catalogue of retrofit interventions for traditional stone houses, organized by building elements and intervention type. It is compiled from multiple sources addressing refurbishment of the building envelope in stone houses across European countries (e.g., Greece, England, Scotland, Austria, Switzerland) under frameworks such as:

IEA Task 59
EU Directive 2018/844
EN 16883:2017

Refurbishment of the envelope in old stone houses requires strategies that preserve both the breathability and original character of the house. Most recommended interventions therefore rely on vapor-open, hygroscopic materials such as wood fiber, hemp, sheep wool, lime plaster, or perlite, which help maintain the thermal mass effect of the thick stone walls while avoiding trapped moisture. Internal insulation is possible where original linings are absent but must be carefully detailed to prevent thermal bridging and condensation, while roof and floor insulation offer significant energy savings if combined with a good ventilation recommended to be at a rate of 0.8 - 1 ACH [1]. Windows are treated as a key heritage element: low-impact strategies such as secondary glazing, glazing replacement, sealing, and shutter repair are preferred, while medium- and high-impact options like internal double glazing or full replica replacement should be considered only with care due to authenticity and cost concerns. Across all measures, reversibility and minimal alteration of historic features are prioritized, with modern impermeable systems avoided.

However, most guidelines primarily focus on envelope interventions, with limited attention to the refurbishment of heating and cooling systems. Both passive and active refurbishment strategies will be tested to evaluate efficiency, including envelope insulation, draft proofing, and heating system modification.

The choice of tested heating systems is based on survey results (section 3.4.4), which indicate that the majority of people install modern heating systems to achieve thermal comfort, especially in mountainous regions such as Douma, and many households supplement the traditional system with a new one, showing the traditional system alone is insufficient.

The following table 5.1.1 is an index of passive refurbishment strategies, some of which will be selected for the simulations and retrofitting strategies proposed.[123], [124], [125], [126], [127], [128]

123 Nicholas Heath, Energy Heritage: A Guide to Improving Energy Efficiency in Traditional and Historic Buildings.

124 Rainer Pfluger et al., Conservation Compatible Energy Retrofit Technologies: Part I: Introduction to the Integrated Approach for the Identification of Conservation Compatible Retrofit Materials and Solutions in Historic Buildings (IEA SHC Task 59, 2021), https://doi.org/10.18777/ieashc-task59-2021-0004.

125 English Heritage, Small-Scale Solar Thermal Energy and Traditional Buildings, 2008.

126 Jesus Rosales Carreon, Review on Techniques, Tools and Best Practices for Energy Efficient Retrofitting on Heritage Buildings (Utrecht University REFOMO, 2015), 45, https://refomo.eu/wp-content/uploads/sites/105/2015/11/Review-on-techniques-for-energy-efficient-retrofitting-of-heritage-buildings_Final.pdf.

127 Maria Boștenaru-Dan et al., "Retrofit of Stone Masonry Buildings in Greece: I. Damage Patterns and Preventive Retrofit/Repair Measures," Buletinul Institutului Politehnic Din Iași LIX (LXIII), no. 2 (2013).

128 Gireesh Nair et al., "A Review on Technical Challenges and Possibilities on Energy Efficient Retrofit Measures in Heritage Buildings," Energies 15 (November 2022): 7472, https://doi.org/10.3390/en15207472.

Table 5.1.1 - Retrofitting Strategies Summary
(Continued on next page)

Source: Author's elaboration based on Heath (Energy Heritage), Pfluger et al. (2021), English Heritage (2008), Rosales Carreon (2015), Boștenaru-Dan et al. (2013), Nair et al. (2022).

Table 5.1.1 - Continued

CATEGORY	STRATEGY	MATERIALS	TECHNIQUE / INSTALLATION	COMMENTS AND RISKS
FINISHING	• Breathable build- up	• Lime mortar • Lime plaster • Limewash	• Maintain or restore original vapor-permeable finishes	• Avoid cement render, gypsum, or plastic paint as they can trap moisture
WALL	• External wall insulation	• Hemp- lime composites (Hempcrete) • Wood fiber panels • Mineral wool • Expanded cork	• Fixed externally with protective breathable finish	• Alters facade • Moisture risk if impermeable
	• External insulation finishing	• Lime- based insulating render with vermiculite	• Applied in 1–2 layers, directly on stone	• Lower performance than board systems • Visually compatible
WALL	• Internal wall insulation	• Wood- fiber boards • Lime plaster • Mineral wool • Sheep wool • Hemp- lime composites • Calcium silicate • Aerogel • Perlite	• Mounted on internal face (timber battens or breathable adhesive) • Hygroscopic, vapor- permeable system is recommended • Consideration of potential condensation from indoor air on the colder side of the insulation	• Condensation • Thermal bridge • Loss of thermal mass • Moisture traps • Usable floor area loss
	• Internal insulation with cavity (with air gap)	• Rigid board insulation	• Separate insulated inner leaf with air gap for ventilation (usually not enough) or sealed (avoid punctures)	• Thermal bridge • Loss of thermal mass • Critical cavity execution
	• Internal insulation with timber batten system	• Cellulose • Mineral wool	• Battens fixed to wall, filled, covered with board	• Needs vapor control • Complex window detailing
	• Solid wood- fiber board system	• Wood fiberboard + lime plaster	• Fully vapor-open • Glued or pinned to wall	• Lower R- values • Even surface required

CATEGORY	STRATEGY	MATERIALS	TECHNIQUE / INSTALLATION	COMMENTS AND RISKS
FLOOR	• Suspended timber floor insulation above	• Mineral wool • Polyurethane boards • Slim- line insulation • Hardboard finish	• Floorboards lifted with care • Mesh netting fixed in place between joists • Insulation laid	• Risk of damaging original floorboards • Potential air leakage if poorly sealed • Increases floor height; adjustments needed to skirting, doors, and sockets
	• Suspended timber floor insulation below		• Insulation fitted between joists • Mesh netting fixed in place	
	• Solid floor insulation		• Remove tiling • Add insulation above the floor • Raise all the elements (doors, sockets...)	
ROOF INSULATION	• Insulation on attic floor or between rafters	• Wood fiber • Cellulose • Mineral wool	• Laid above ceiling or between rafters	• Needs airtight detailing • Ventilation needed to avoid overheating
WINDOW RETROFIT	• Secondary glazing • Window seals • Low- emissivity coatings • Shutter repair	• Internal glazed panels (Low- E) • New timber replica sashes • Secondary panels • Heavy curtains	• Mounted on interior • Minimal intervention	• Condensation risk • Visual impact
HEATING AND COOLING	• Electric or hydronic systems	• Heat pumps • Radiant panels • Underfloor heating	• Integrated: Underfloor (embedded in screed) • Surface mounted: Radiant panels on wall	• Floor height changes • Invasive installation
VENTILATION STRATEGIES	• Mechanical ventilation with heat recovery (MVHR)	• Compact ventilation units (MVHR units)	• Ducted or wall-mounted	• Duct routing in old structure • Needs airtight envelope to be effective
SMART CONTROL	• Energy management systems (BMS) • Smart thermostats	• Digital sensors • Programmable controls	• Installed with minimal wiring	• Visibility of sensors • User acceptance

Table 5.1.1 - Continued

CATEGORY	STRATEGY	MATERIALS	TECHNIQUE / INSTALLATION	COMMENTS AND RISKS
MOISTURE CONTROL	• Hygrothermal monitoring • Breathable systems (Moisture-aware detailing)	• Wood fiber • Lime plaste	• No vapor barriers • Monitor RH	• Essential to avoid mold or decay • Condensation and mold at bridges or edges
THERMAL BRIDGE CONTROL	• Thermal bridge reduction	• Hygroscopic systems	• Extend insulation to window reveals, floor-wall junctions • Use continuous layers, insulated battens, or thermal breaks	• Risk of decay at weak points (doors, windows reveals, structure and wall junction)
LIGHTING RETROFIT	• Retrofit to LED	• LED	• Non- invasive retrofit	• Minimal risk
SOLAR INTEGRATION	• Photovoltaics • Solar Thermal	• PV tiles • Solar slates • Custom roof- integrated modules	• Discreet or flush- mounted systems (roof or facade) • Mount on less visible areas	• Visual impact • Structural load
AIR TIGHTNESS	• Air sealing	• Airtight membranes • Tapes	• Requires careful detailing	• Combine with ventilation • Moisture management needed
MATERIAL SELECTION	• Reversible systems • Avoidance of impermeable materials	• Wood fiber • Lime based plaster • Avoid closed-cell foam, plastic insulation, cement renders	• Avoid impermeable or cement- based materials • Use vapor- open materials	• Moisture accumulation • Mold • House damage

Table 5.1.2 is developed to detail material properties, provide references and sources, and clarify market availability of materials used in simulations.

However, not all materials in the table will be included in the sensitivity simulations (due to similarity, cost, or unavailability in Lebanon).[129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143]

Table 5.1.2 - Material Properties and Description for Retrofit (Continued on next page)

Source: Author's elaboration based on [129 - 143]

129 Ferrimix Bio Lime FC15 – Natural Hydraulic Lime Plaster – Technical Data Sheet (Ferrimix s.r.l., 2021), https://www.ferrimix.it/wp-content/uploads/2016/11/TDS-FC15-FERRIMIX.pdf.

130 Insulating Hemp Lime Plaster (Bio Beton®500 Venezia) – Technical Data Sheet (GráHemp Building Limited, n.d.), https://grahemp.ie/products/insulating-hemp-lime-plaster-single-bucket.

131 IsoHemp S.A., Technical Data Sheet – IsoHemp Hemp Block (IsoHemp S.A., 2024), https://www.isohemp.com/fr.

132 BetonWood, "Wood Fibre Board Products Catalogue," https://www.woodfibreboard.com/wood-fibre-board-catalogue.html.

133 Knauf Insulation – Mineral Wool 35: Technical Data Sheet (Knauf Insulation S.p.A., 2024), https://knauf.com/it-IT/p/prodotto/mineral-wool-35-21509_4062.

134 IW Technical Datasheet – Optimal Sheep Wool Insulation 18 Kg/M3 (Isolena Naturfaservliese GmbH, 2025), https://www.isolena.com/en/sheepwoolinsulation-optimal/.

135 "CorkLink - Expanded Cork," Cork Products Direct from Portugal, n.d., https://www.corklink.com/index.php/expanded-cork/.

136 The Vermiculite Association, Vermiculite Data – Exfoliated Vermiculite Properties (The Vermiculite Association, 2014), https://www.vermiculite.org/.

137 PROMATECT®-H Calcium Silicate Board – Technical Data Sheet, V01R02 – 14/05/2012 (Promat International N.V., 2016), https://www.promat.com/en.

138 Aerogel A2 – Thermal Insulation for Construction (Aerogel.it (ECOFINE S.r.l.), 2024), https://www.aerogel.it/scheda-informativa-en/.

139 Ecocel Cellulose Insulation – Technical Data (Ecocel Ltd., n.d.), https://www.ecocel.ie/wp-content/uploads/2017/10/Ecocel_tech.-data_Oct2017.pdf.

140 Thermal Insulation Materials: Polyurethane Foam – Technical Data Sheet (DOW Chemical Company, 2017), https://highperformanceinsulation.eu/wp-content/uploads/2016/08/Thermal_insulation_materials_made_of_rigid_polyurethane_foam.pdf.

141 Apache Tables – Thermal Conductivity, Specific Heat Capacity and Density, Table 6 (part of Apache Tables series) (Glasgow, UK, 2011), https://help.iesve.com/ve2021/table_6_thermal_conductivity__specific_heat_capacity_and_density.htm.

142 PERODIC® Fine Grade Expanded Perlite – Technical Data Sheet, ST 03eng 97.14 (Perlite Italiana S.r.l., 2021), https://www.perlite.it/.

143 EAD 040011-00-1201 – Vacuum Insulation Panels (VIP) with Factory Applied Protection Layers (European Organisation for Technical Assessment (EOTA), 2017), https://www.eota.eu/.

Table 5.1.2 - Continued

MATERIAL	DESCRIPTION	CONDUCTIVITY λ (W/m.K)	SPECIFIC HEAT CAPACITY (J/kg.K)	DENSITY (kg/m³)	TYPICAL THICKNESS (mm)
Lime Plaster	• Breathable natural wall coating made from lime and sand	0.54	850	1400	10 -20
Hemp-Lime	• Mix of hemp shives and lime • Breathable and insulating plaster	0.12	1330	500	30 - 50
Hempcrete	• Lightweight insulating concrete blocks made from hemp and lime	0.087	1000 -1700	320	7.5 - 9 - 12 - 15 - 20 - 25 - 36
Wood fiber board	• Rigid boards from compressed wood fibers • Good for walls and roofs	0.036	2100	60	20 - 30 - 40 - 50 - 60 - 80 - 100 - 120 - 140 - 160 - 180 - 200 - 220 - 240
		0.040		140	40 - 120 - 140 - 160 - 180 - 200
		0.045		210	35 - 40
		0.043		180	52 - 60 - 80 - 100
		0.038		160	20 - 30
Mineral wool	• Fibrous insulation made from rock or slag; fire-resistant.	0.040	1030	18	25 - 30 - 40 - 50 - 60 - 70 - 80 - 100 - 120
Sheep wool	• Natural, breathable insulation made from real sheep's wool	0.038	1760	18	30 - 40 - 50 - 60 - 80 - 100 - 120 - 140
Expanded cork	• Semi-rigid cork sheets that expand and contract	0.036 - 0.040	1670	105 - 125	10-20-30-40-50-60 to 300 (slabs)
Vermiculite	• Hydrated magnesium-aluminum-iron silicate, that expands when heated (lightweight, absorbent, fire-resistant) • Pairs well with lime based renders	0.058	840	56 - 64	10 - 25 mm (plaster mix) 50 - 150 (insulation)
		0.064		80 - 96	
		0.071	1080	160 - 192	
Calcium silicate	• Rigid, breathable board that absorbs moisture and insulates.	0.175	850	870	6 - 8 - 10 - 12 - 15 - 20 - 25
Aerogel panel (Slimline insulation)	• Ultra-light, high-performance insulation • Very thin and efficient.	0.016	1030	180 - 220	10 – 40
Cellulose	• Recycled paper fibers treated for fire-resistance • Blown-in or packed	0.040	1600	35 - 40	100 -150 - 200 - 250 - 300
Polyurethane PUR boards (Slim-line insulation)	• Closed-cell rigid foam boards • Very efficient thermal insulator	0.025	1500	30	105
Hardboard finish	• Thin, smooth wooden board used to cover floor insulation	0.144	1381	1010	3 - 3.5 - 5.5
Perlite	• Insulation made of natural volcanic glass that expands when heated (lightweight and porous) • Can't be used over radiant heating panels	0.040 0.080 - 0.160	837	50 - 60	22
Vacuum Insulated Panels (VIP)	• Very thin insulating boards used in thigh spaces or in heritage buildings • Made of pressed fumed silica	0.0043 - 0.008	800 - 1000	180 - 250	10 - 60
Rockwool	• Rigid insulation (used for exterior)	0.038	840	128	50

5.2 SENSITIVITY ANALYSIS METHOD AND RESULTS

Based on Tables 5.1.1 and 5.1.2 of the previous Section 5.1, we are able to carefully select and classify the different retrofitting methods according to their level of impact on the building (Table 5.2.1). These methods were then evaluated through a sensitivity analysis using a one-at-a-time (OAT) approach (Figure 5.2.1 and 5.2.2): starting from the base case (Case N) and changing one variable at a time while keeping all the others constant. After each test, the model is reset to the base case before modifying the next variable.

	MODIFICATIONS	Values GF	Values 1st Floor	IMPACT
CASE S	TSBL Guidelines	0.77	0.77	-
N1	-	0.98	1.82	LOW
O-1.1	Mix Case N + Case S (only the N/S walls of the 1st floor use insulation from Case S to match the U-value of other walls = 0.981)	0.98	1.82	LOW
O-1.2	ACH = 1.3	0.98	1.93	LOW
O-1.3	Hemp lime plaster 35mm	0.76	1.22	LOW
N2	-	2.49	2.49	LOW
O-2.1	Wood fiber 80mm (between rafters)	0.67	0.67	LOW
O-2.2	Insulated attic floor with mineral wool 120mm	0.28	0.28	LOW
O-2.3	Case 2.1 + 2.2	0.50	0.50	LOW
N3	Single clear	5.89	5.89	LOW
O-3.1	Better single glazing	5.00	5.00	LOW
N4	Very low solar control	0.91	0.91	LOW
O-4.1	Low solar control	0.70	0.70	LOW
N5	-	2.21	1.85	LOW
N6	-	2.79	2.79	LOW
N7	-	12.00	12.00	LOW
O-7.1	LED Lights Power Density = 5	5.00	5.00	LOW
N8	-	1.00	1.00	LOW
O-8.1	Closed shutters W-E	0.31	0.31	LOW
O-8.2	90 degrees closed shutters W-E	0.66	0.66	LOW
O-8.3	Closed shutters - S	0.86	0.86	LOW
O-8.4	O-8.1 + O-8.3	0.18	0.18	LOW
N9	Sobia (wood)	0.54	0.54	LOW
O-9.1	New efficient Sobia (stove)	0.70	0.70	LOW
O-9.2	New efficient Sobia (stove)	0.85	0.85	LOW

O-1: U-value (W/m².K)
O-2: U-value (W/m².K)
O-3: U-value (W/m².K)
O-4: g-value
O-5: U-value (W/m².K)
O-6: U-value (W/m².K)
O-7: Power Density (W/m²)
O-8: Shading Ratio
O-9: Efficiency
O-10: Efficiency

Table 5.2.1 - Index of Tested Variables, U-Values, and Resulting Impact

Source: Author's elaboration

This allows us to isolate the effect of each input on the energy and comfort results, enabling a clear comparison of their relative influence.

The following Table 5.2.1 is the variable index to the sensitivity analysis that was conducted in Figures 5.2.1 and 5.2.2. It provides us with an overview of the different variants tested and their impact on the building, as well as their respective U-values.

	MODIFICATIONS	Values GF	Values 1st Floor	IMPACT
O-1.4	Wood fiber 40mm	0.50	0.50	MEDIUM
O-1.5	Aerogel slim line 10mm	0.60	0.60	MEDIUM
O-1.6	Aerogel slim line 20mm	0.44	0.44	MEDIUM
O-1.7	Calcium silicate board 25mm	0.44	0.44	MEDIUM
O-3.2	Case S (double glazing)	4.00	4.00	MEDIUM
O-3.3	Old double glazing	3.00	3.00	MEDIUM
O-3.4	Modern double glazing	1.60	1.60	MEDIUM
O-4.2	Medium solar control	0.50	0.50	MEDIUM
O-6.2	Vacuum insulation panel 20mm	0.31	0.31	MEDIUM
O-10.4	Window split AC (low)	1.12	1.12	MEDIUM
O-10.5	Basic fixed-speed split AC (med eff)	1.47	1.47	MEDIUM
O-10.6	Inverter split AC (high eff)	1.93	1.93	MEDIUM
O-5.1	Intermediate floor insulation with mineral wool 50mm	1.05	1.05	MEDIUM/HIGH
O-5.2	O-5.1 + Attic floor mineral wool 50mm	0.56	0.56	MEDIUM/HIGH
O-5.3	O-5.1 + O-2.2	0.43	0.43	MEDIUM/HIGH
O-5.4	Roof O-5.2 + VIP 10mm	0.56	0.56	MEDIUM/HIGH
O-5.5	Rockwool high density 30mm	0.22	0.22	MEDIUM/HIGH
O-5.6	Rockwool high density 30mm + roof mineral wool 50mm	0.33	0.33	MEDIUM/HIGH
O-1.8	Exterior rockwool insulation GF 140mm	0.19	0.19	HIGH
O-2.4	Roof external insulation	0.19	0.19	HIGH
O-3.5	High perf triple glazing	0.90	0.90	HIGH
O-3.6	Passive house	0.60	0.60	HIGH
O-4.3	High solar control	0.30	0.30	HIGH
O-4.4	Very high solar control	0.20	0.20	HIGH
O-6.1	Mineral wool 40mm	0.74	0.74	HIGH
O-10.1	Radiator (Electric Boiler)	0.95	0.95	HIGH
O-10.2	Radiator (Heat pump)	1.93	1.93	HIGH
O-10.3	Underfloor heating / Radiant wall panels (Heat pump)	2.18	2.18	HIGH

The results made it clear that the extent of improvement strongly depends on the type of intervention. Envelope upgrades alone provide only a limited reduction in primary energy, while the choice of heating system shapes the overall performance. In fact, as mentioned in section 4.5.4, the unsuitable choice of system can even increase energy demand compared to the baseline Case N.

By grouping all tested measures according to their relative impact (Table 5.2.1), three potential bundles of retrofit strategies emerge.

1- The **low-impact bundle** preserves the house with minimal interventions but yields limited improvements.

2- The **moderate-impact bundle** achieves a more balanced trade-off between performance and heritage compatibility.

3- The **high-impact bundle** delivers the best results in terms of performance and comfort, but at the cost of interventions that completely modify the character of the house. Therefore, the high-impact bundle is considered only as a hypothetical scenario, serving to illustrate the potential performance of a fully passive house compared to the traditional typology.

The results of the OAT simulations are compiled into sensitivity graphs for each floor (Figures 5.2.1 and 5.2.2). These visualizations highlight which strategies have the most effect on the primary energy demand (Y-axis, in kWh/m2/year), relative to the normalized value of the tested variable (X-axis, e.g. U-value, g-value, system efficiency, light power density...).

For clarity, the variables are divided into categories (walls, roof, windows U-value, windows g-value, etc.) and normalized to provide a common comparison basis. In addition, each variable is also assigned to a group (low, moderate, high) according to the intensity of its impact on the original building. This classification ensures that the intervention proposals can be prioritized both by their effectiveness and by their level of intrusion on the existing structure.

As we can notice, both the ground floor (Figure 5.2.1) and the first floor's sensitivity results (Figure 5.2.2) reveal different influences on the primary energy demand according to the impacts. While parameters such as envelope insulation and window performance shape the baseline efficiency, it is heating system-related modifications that make a major difference.

By interpreting these results in the next Section 5.3, we will group the measures according to their impact, which provides a structured basis for the proposed retrofitting bundles.

Figure 5.2.1 - Sensitivity Analysis Results of the Ground Floor (Right)

Figure 5.2.2 - Sensitivity Analysis Results of the First Floor (Continued on next page)

Source: Author's elaboration

Figure 5.2.1

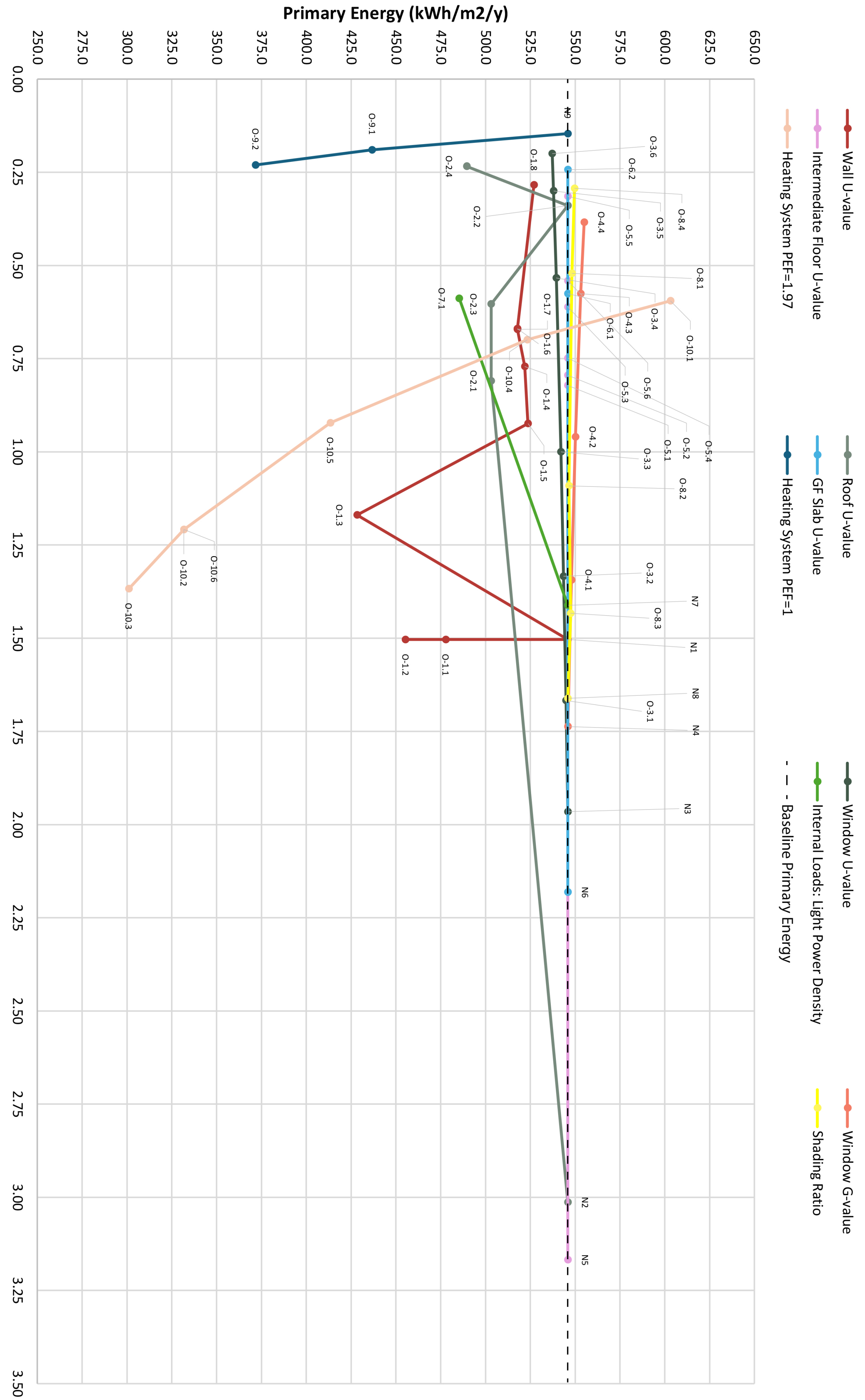
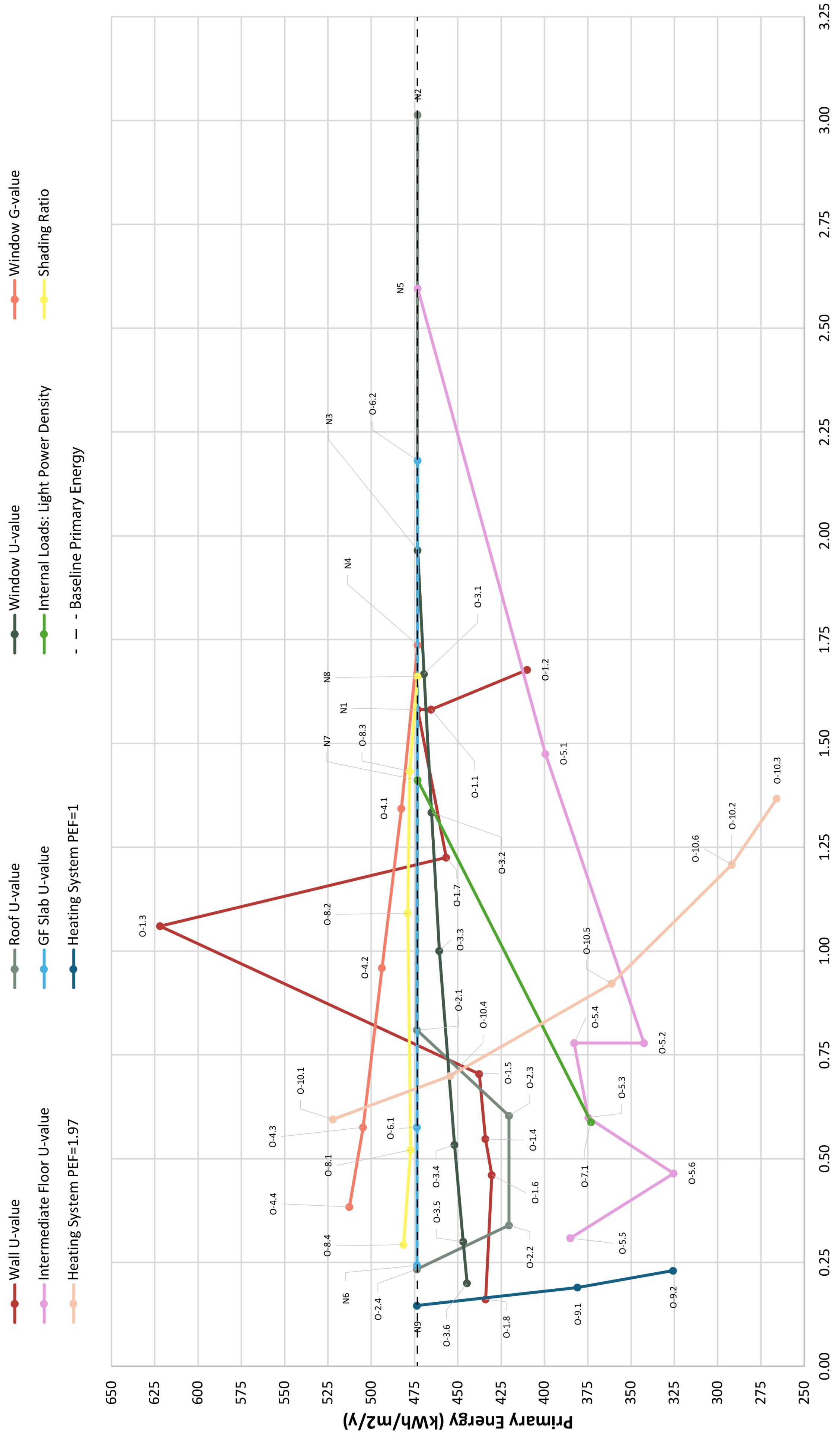


Figure 5.2.2 - Continued



5.3 CONSOLIDATED INTERVENTION SCENARIOS

After identifying the most effective individual measures through the sensitivity analysis, the next step is to consolidate the most efficient solutions into full-house intervention bundles. By grouping all the testing solutions according to their impact, we create bundles of refurbishment strategies with different impacts on the house according to restoration guidelines from around the world since there are no specific laws on how to properly restore the traditional house in Lebanon.

For each impact category, the most efficient solutions per variable and per floor were combined together in order to simulate the performance of a house after a coherent retrofit package (Tables 5.3.1.1, 5.3.2.1, 5.3.3.1). This means that all low-impact measures were grouped together in one scenario, all moderate-impact measures into another, and all high impact measures into a third. Each bundle was then tested, allowing us to assess the overall impact on the entire building and the occupants' comfort rather than isolated variables. The results were evaluated in terms of annual thermal discomfort (heat stress, %) and primary energy consumption, providing a clear comparison of the performance of each bundle.

Finally, the consolidated bundles were compared to Case N (baseline with heating) and Case S (TSBL retrofit), highlighting the degree of improvement achieved at each level of intervention, and guiding the selection of preferred strategies.

The results serve two main purposes: First, they confirm that refurbishing only the envelope yields only a small margin of improvement. Second, they show that by upgrading the heating system, we see a significant difference in the final primary energy use. When refurbishing the heating system, the difference in impact lies in how we refurbish it, because as proved in some cases, choosing an inappropriate heating system such as option O-1.8 (Figure 5.2.1 and 5.2.2) can lead to an increase in the primary energy compared to the base case with a traditional sobia stove.

In summary, the consolidated intervention bundles make it possible to compare the margins of change between low, moderate and high retrofit approaches, providing a basis for evaluating not only the performance outcomes but also the appropriateness of each level of intervention in the context of heritage preservation.

5.3.1 LOW IMPACT BUNDLE

Once the low-impact measures were identified (Table 5.2.1), the most efficient options were selected from the sensitivity results (Figures 5.2.1 and 5.2.2) and then organized in the following Table 5.3.1.1.

As illustrated in the sensitivity analysis of the ground floor and the first floor (Figures 5.2.1 and 5.2.2), very light intervention, such as draft proofing the house proved to have a very high impact on the performance of the house. In addition, hemp lime plaster was applied as a finishing layer which is both a breathable and insulating plaster, making it suitable for old sandstone houses and commonly used in heritage retrofitting. All the following modifications correspond to the retrofit strategies summarized in Table 5.1.1, with the materials and their properties detailed in Table 5.1.2.

The roof is insulated with natural breathable materials and is fully reversible. As seen in the sensitivity graph, wood fiber between rafters and a mineral wool on the attic floor were the best fitting options for the low impact intervention.

For the windows, only a new clear single glazing and sealing are required to improve the U-value; since the solar gains benefit the house, it is important to maintain a high Solar Heat Gain Coefficient (SHGC). To further enhance performance, the windows are repositioned towards the internal part of the wall.

The intervention on the intermediate floor and the ground floor slab are considered a medium- to high-impact solution, since insulating them would require damaging the existing tiles and adding new layers. To preserve authenticity, they are therefore kept uninsulated and in their original state, unless there was need to replace the tiles (damaged floor, cracked tiles).

The lighting system, however, is entirely upgraded, replacing inefficient halogen fixtures with efficient LED lights.

The sensitivity results also show that additional shading tends to worsen energy performance by blocking useful solar gains. For this reason, shading is only applied for glare control at specific times of the day.

Finally, the traditional sobia stove is replaced with a more efficient model, still operating on wood as fuel, thus improving system efficiency while maintaining cultural continuity and independency from the public energy grid.

The following modifications on the house are illustrated in a section in Figure 5.3.1.1 (scale 1/100).

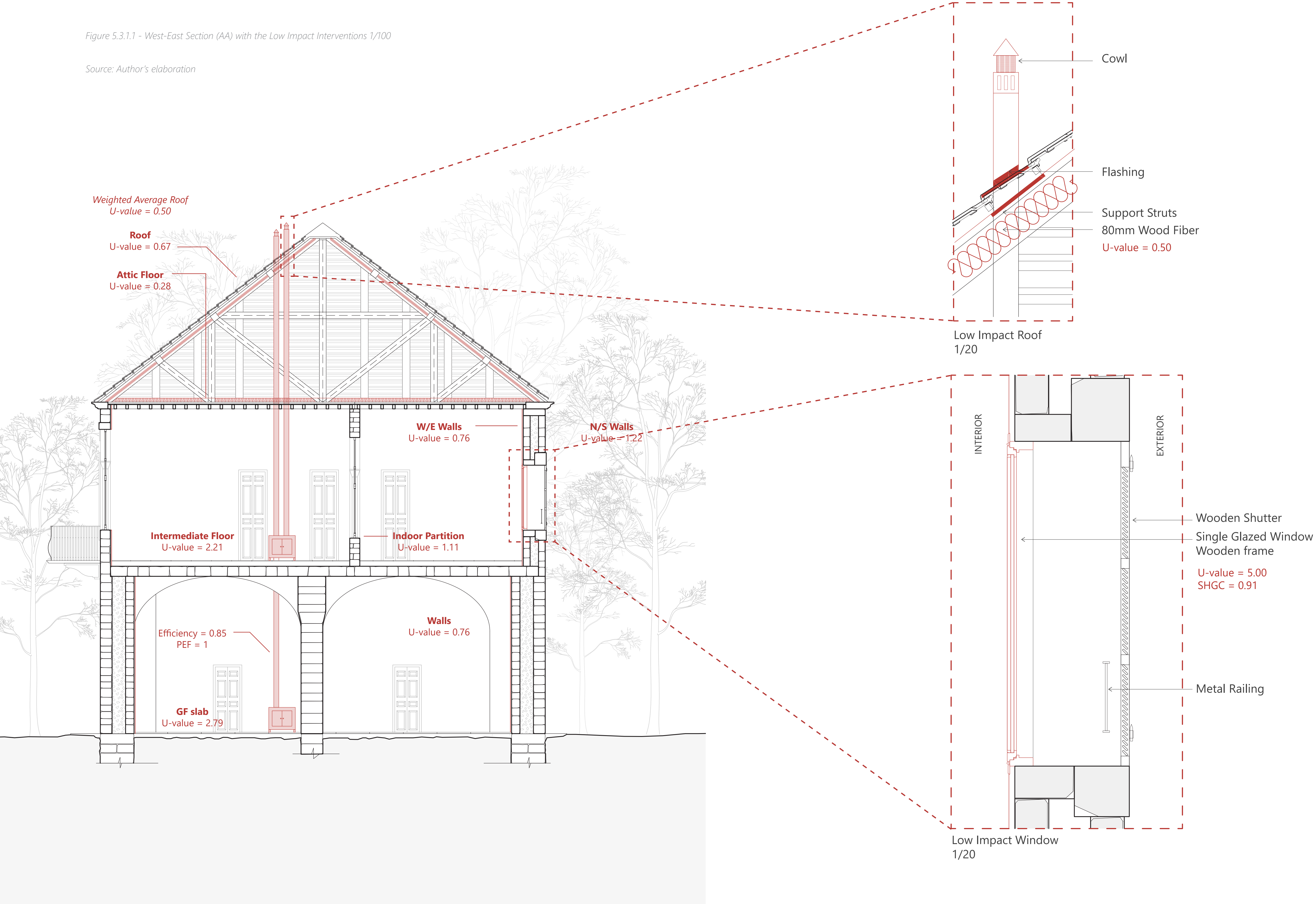
Table 5.3.1.1 - Consolidated Low Impact Scenario

Source: Author's elaboration

	LOW IMPACT				
	Building Element	**GF**	**Intervention**	**1st Floor**	**Intervention**
PASSIVE	**Wall**	O-1.3 O-1.2	*Hemp lime plaster (35mm) ACH = 1.3*	O-1.2	*ACH = 1.3*
	Roof	O-2.3	*Roof: wood fiber 80mm (between rafters) Insulation attic floor: mineral wool 120mm*		
	Window U-value	O-3.1	*Better Single Glazing U-value = 5*	O-3.1	*Better Single Glazing U-value = 5*
	Window g-value	N4	*Very Low Solar Control (SHGC = 0.91)*	N4	*Very Low Solar Control (SHGC = 0.91)*
	Intermediate Floor	N5	*No insulation*		
	GF slab	N6	*No insulation*		
	Internal Loads	O-7.1	*Lights Power Density = 5 W/m²*	O-7.1	*Lights Power Density = 5 W/m²*
	Shading	N8	*No shading*		*No shading*
ACTIVE	**Heating**	O-9.2	*New efficient Sobia Efficiency = 85% PEF = 1 (wood)*		*New efficient Sobia Efficiency = 85% PEF = 1 (wood)*

Figure 5.3.1.1 - West-East Section (AA) with the Low Impact Interventions 1/100

Source: Author's elaboration



5.3.2 MODERATE IMPACT BUNDLE

Once the moderate-impact measures were identified (Table 5.2.1), the most efficient options were selected from the sensitivity results (Figures 5.2.1 and 5.2.2) and then organized in the following Table 5.3.2.1.

Slim line insulation is added and covered with plaster, which significantly improves the performance of the wall (U-value = 0.53 compared to baseline wall U-value = 1.82, and low impact wall U-value = 1.22).

The roof is insulated together with the attic floor, using the same reversible approach as the low-impact bundle, since no other option was more efficient except one measure included in the high-impact bundle.

The windows are entirely replaced with a modern low-e double glazing and a new frame, combined with a medium solar control to limit the excessive heat gains and glare. As in the previous bundle, the windows are repositioned towards the internal part of the wall.

The intermediate floor is insulated and re-tiled with terracotta tiles in a traditional style, which remain commonly available in Lebanon but come at a slightly higher cost than modern alternative.

The ground floor slab is kept uninsulated, since no measurable improvements were recorded in the sensitivity analysis.

Shading continues to worsen the energy performance by blocking useful solar gains and is therefore only used for glare protection at specific times of the day.

The active heating system is replaced: the traditional sobia stove is substituted with an inverter AC unit with both hot and cold function. The unit is positioned on the north or east wall (avoiding the main facades west and south), with installation including a pipe routing through the wall, sealing it with spray foam, and adding a water drain along the facade. However, another option for the heating system would be a wall-hung radiator with pipes running along the walls in order not to damage any tiles.

Finally, the air change rate (ACH) is reduced to 1.3 by sealing cracks and incorporating the insulation, plaster, and new windows.

The following modifications are illustrated in a section in Figure 5.3.2.1 (scale 1/100).

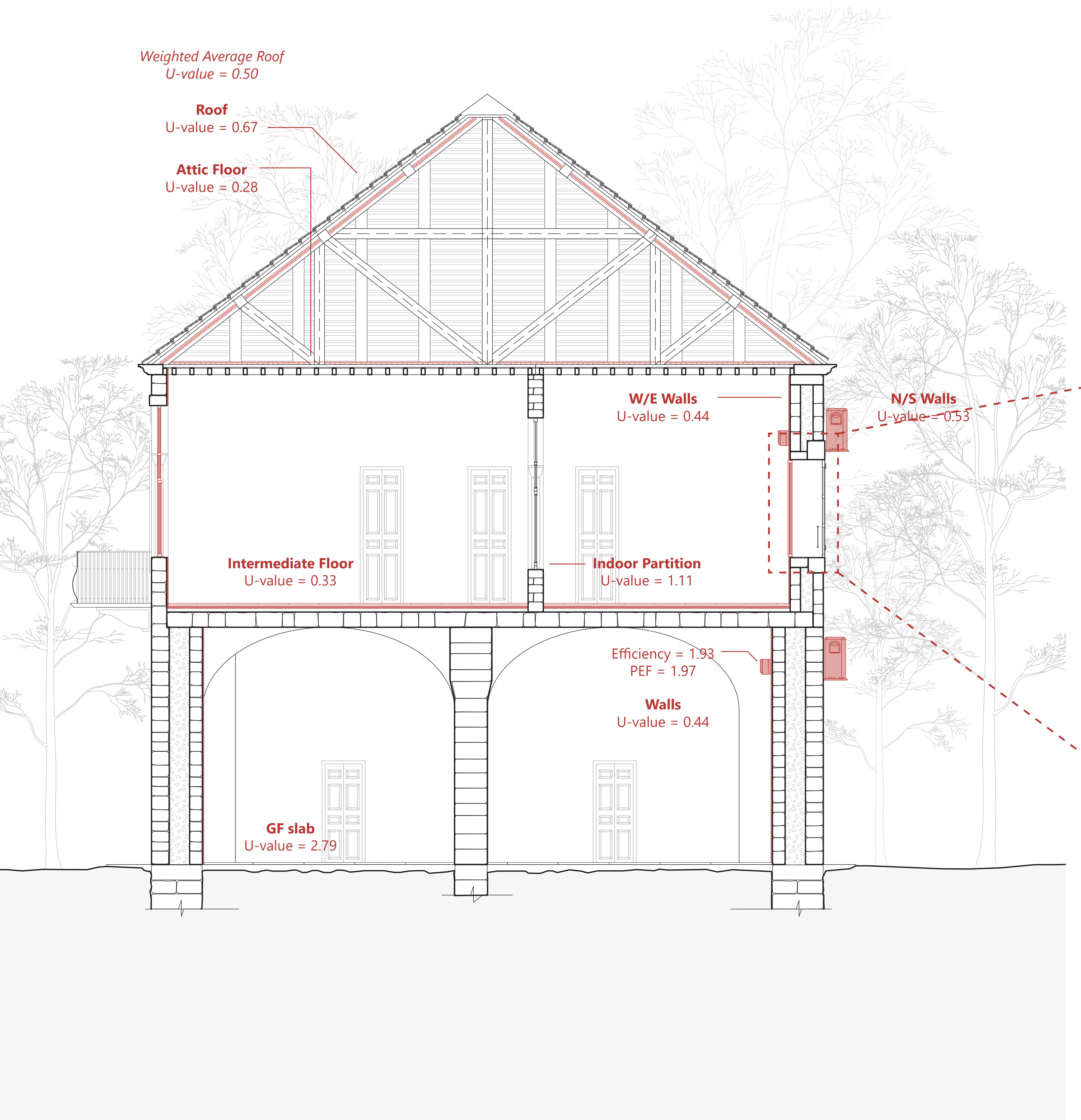
5.3.2.1 - Consolidated Moderate Impact Scenario

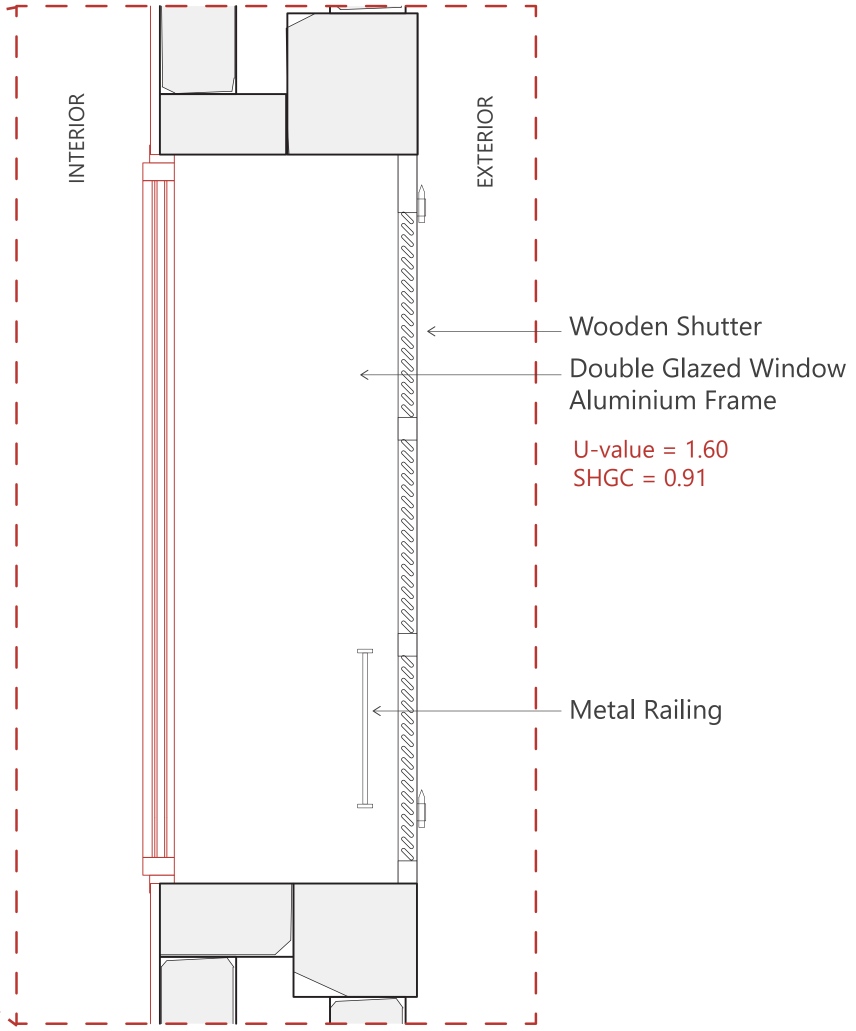
Source: Author's elaboration

	MODERATE IMPACT				
	Building Element	**GF**	**Intervention**	**1st Floor**	**Intervention**
PASSIVE	**Wall**	O-1.6 O-1.2	*Aerogel Slim Line 20mm ACH = 1.3*	O-1.6 O-1.2	*Aerogel Slim Line 20mm ACH = 1.3*
	Roof	O-2.3 variant	*Roof: wood fiber 80mm (between rafters) Insulation attic floor: mineral wool 50mm*		
	Window U-value	O-3.4	*Double Glazing U-value = 1.6*	O-3.4	*Double Glazing U-value = 1.6*
	Window g-value	N4	*Very Low Solar Control (SHGC = 0.91)*	N4	*Very Low Solar Control (SHGC = 0.91)*
	Intermediate Floor	O-5.6	*Intermediate floor: mineral wool 50mm Attic floor: mineral wool 50mm*		
	GF slab	N6	*No insulation*		
	Internal Loads	O-7.1	*Lights Power Density = 5 W/m²*	O-7.1	*Lights Power Density = 5 W/m²*
	Shading	N8	*No shading*	N8	*No shading*
ACTIVE	**Heating**	O-10.6	*Efficiency = 1.93 PEF = 1.97*	O-10.6	*Efficiency = 1.93 PEF = 1.97*

Figure 5.3.2.1 - West-East Section (AA) with the Moderate Impact Interventions 1/100

Source: Author's elaboration





Low Impact Window
1/20

5.3.3 HIGH IMPACT BUNDLE

The high-impact case is presented as a hypothetical scenario and not recommended, since it alters the original characteristics of the house too extensively. It could, however, become a viable option in cases where the house is severely damaged and must be completely rebuilt with new sandstones, and if this approach falls within the budget of the house owner. All the following modifications correspond to the retrofit strategies summarized in Table 5.1.1, with the materials and their properties detailed in Table 5.1.2.

An external insulation is applied together with a new stone cladding that mimics the original facade. The roof is completely rebuilt by adding external insulation and re-tiling it with the terracotta roof tiles, which are commonly found in Lebanon. The attic floor is additionally insulated in a reversible way with mineral wool.

The windows are replaced with triple-glazed passive-house grade windows, repositioned on the internal side of the wall, and equipped with high solar control to reduce glare. While this measure enhances thermal performance, it also reduces passive solar gains, thereby increasing heating demand.

The intermediate floor is insulated with rockwool and re-tiled, and an advanced, more invasive but efficient active heating system is introduced. The selected system is underfloor heating, which delivers the highest efficiency and comfort. Radiant panels can also be added to the rooms for additional localized heating when required.

The lighting system is modernized by replacing all existing fixtures with highly efficient LED lights.

As in the previous bundles, shading continues to worsen the energy performance by blocking beneficial solar gains and therefore is only used for glare control at specific times of the day.

The following modifications are illustrated in a section in Figure 5.3.3.1 (scale 1/100).

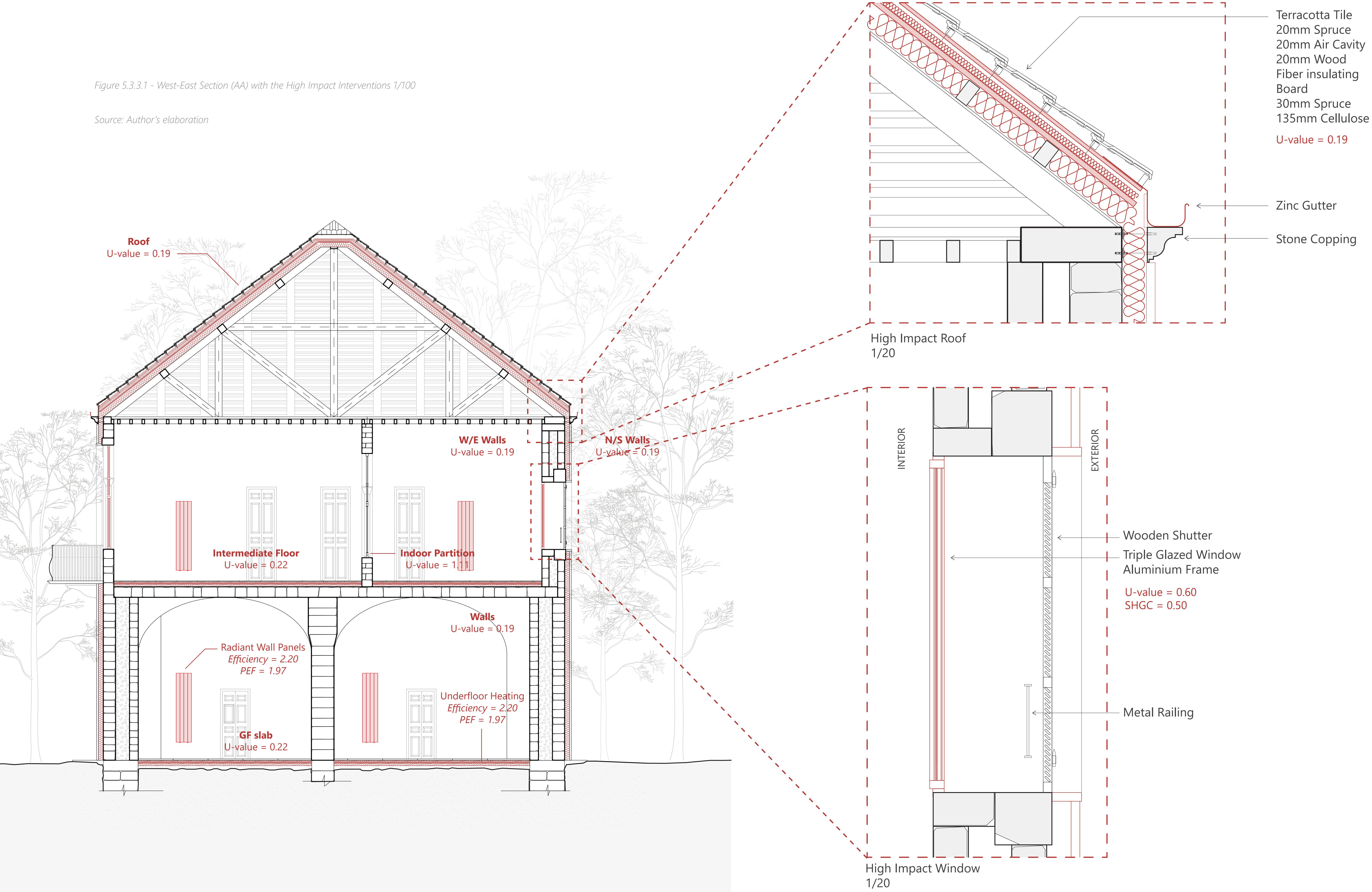
5.3.3.1 Consolidated High Impact Scenario

Source: Author's elaboration

	HIGH IMPACT				
	Building Element	**GF**	**Intervention**	**1st Floor**	**Intervention**
PASSIVE	**Wall**	O-1.8 O-1.2	*Exterior Rockwool Insulation 140mm ACH = 1.3*	O-1.8 O-1.2	*Exterior Rockwool Insulation 140mm ACH = 1.3*
	Roof	O-2.4	*Roof: external insulation Attic floor: mineral wool 50mm*		
	Window U-value	O-3.6	*Triple Glazing U-value = 0.6*	O-3.6	*Triple Glazing U-value = 0.6*
	Window g-value	O-4.2	*Medium Solar Control (SHGC = 0.5)*	O-4.2	*Medium Solar Control (SHGC = 0.5)*
	Intermediate Floor	O-5.5	*Intermediate floor: Rockwool high density 30mm*		
	GF slab	O-5.5	*Rockwool high density 30mm*		
	Internal Loads	O-7.1	*Lights Power Density = 5 W/m²*	O-7.1	*Lights Power Density = 5 W/m²*
	Shading	N8	*No shading*	N8	*No shading*
ACTIVE	**Heating**	O-10.3	*Efficiency = 2.20 PEF = 1.97*	O-10.3	*Efficiency = 2.20 PEF = 1.97*

Figure 5.3.3.1 - West-East Section (AA) with the High Impact Interventions 1/100

Source: Author's elaboration



5.3.4 FINAL BUNDLE COMPARISON

Case N, the baseline scenario, exhibits the highest energy demand, despite relying on wood as a heating fuel. The low-impact bundle already sees a noticeable improvement with very minimal intervention, while still maintaining a wood-fueled heating system. Moderate- and high-impact interventions achieve further reductions, with the high-impact option performing best in terms of energy and comfort, though at the cost of irreversible and invasive changes to the character of the house.

Case N (Baseline with heating):
High primary energy demand (≈ 550–600 kWh/m²·y).
Discomfort (hot stress) ≈ 11–12%.

Represents the inefficient sobia stove system with no envelope retrofit.

Case S (TSBL retrofit):
Primary energy reduced to ≈ 450 kWh/m²·y.
Discomfort slightly lower ≈ 9–10%.

Shows modest improvement due to envelope insulation and reduced infiltration, but still high overall demand.

Low Impact bundle:
Primary energy ≈ 400 kWh/m²·y.
Discomfort ≈ 8%.

Demonstrates incremental gains with minimal intervention.

Moderate Impact bundle:
Primary energy drops significantly to ≈ 250–300 kWh/m²·y.
Discomfort reduced to ≈ 6–7%.

Provides the best compromise between energy savings and comfort improvements without altering the house drastically.

High Impact bundle:
Primary energy reduced to ≈ 180–200 kWh/m²·y.
Discomfort nearly halved, ≈ 5–6%.

This is the best performance, but it comes at the cost of intrusive interventions that compromise the heritage character and is not recommended.

In conclusion, while the high impact bundle achieves the greatest technical performance, the moderate impact bundle emerges as the most viable compromise, balancing energy and comfort improvements with heritage compatibility. In summary, we obtain the following results:

Case N vs Case S: ~20% energy savings, with only ~2% reduction in discomfort.
Case N vs Low Impact: ~30% energy savings, ~ 3% reduction in discomfort.
Case N vs Moderate Impact: ~55–60% savings, ~ 5% reduction in discomfort.
Case N vs High Impact: ~70%+ savings, ~ 6–7% reduction in discomfort.

The first graph illustrates the relation between thermal discomfort and primary energy demand per year. It clearly shows the progressive shift from the basline Case N towards the low, moderate, and high impact bundles. Case N sits at the extreme end with the highest energy demand and a moderate discomfort, while the high-impact bundle sits at the lowest end of the graph, indicating the lowest values. Importantly, all retrofit cases remain below the threshold recommended by ASHRAE (Section 3.4.1), indicating that even minimal interventions help maintain acceptable comfort levels.

The second graph (Figure 5.2.4.2) directly compares energy savings against discomfort reduction, highlighting the efficiency of each bundle. It shows that the moderate-impact case achieves the best balance, offering significant

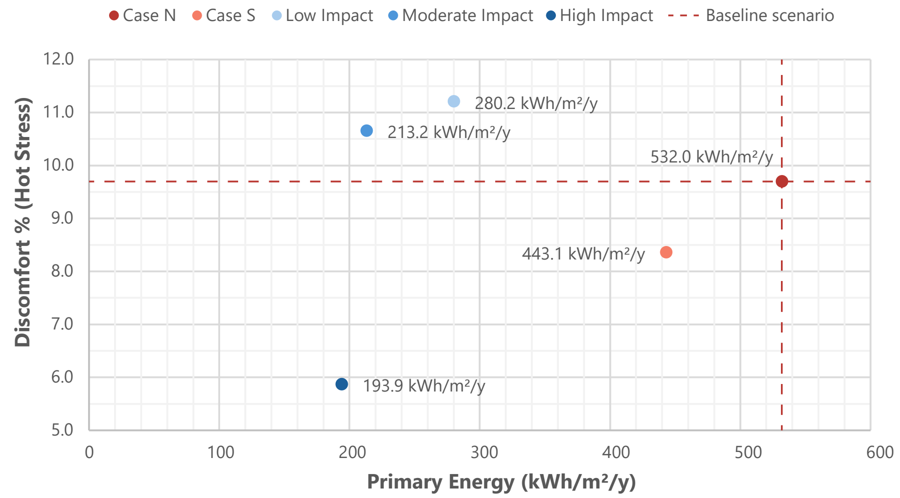


Figure 5.3.4.1 - Discomfort vs Primary Energy

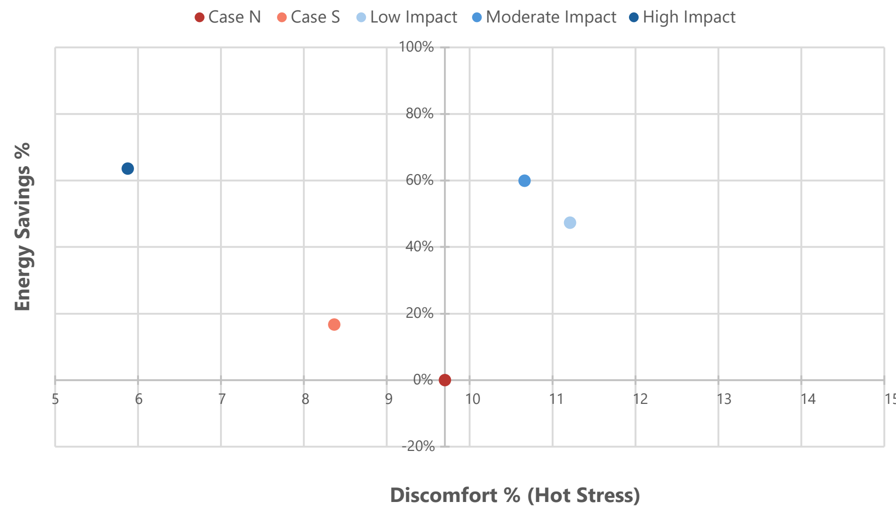


Figure 5.3.4.2 - Energy Savings vs Discomfort

Source: Author's elaboration

reductions in both energy demand and discomfort without the irreversible changes required in the high-impact option.

To complement the annual results, Figures 5.3.4.3 to 5.3.4.7 present the distribution of primary energy per month in kWh/m² for each case. The graph distinguishes between lighting, equipment, and heating loads, allowing for an understanding of the influence of different interventions on the energy performance. While Case N is characterized by high heating peaks in the winter months, Case S and the low-impact bundle show modest reductions. In contrast, the moderate and high-impact bundles flatten the seasonal curve, but since these two bundles don't show a too important reduction, the moderate bundle is considered most appropriate.

Together, these findings set the stage for the following cost analysis, which assesses the practical feasibility of each bundle.

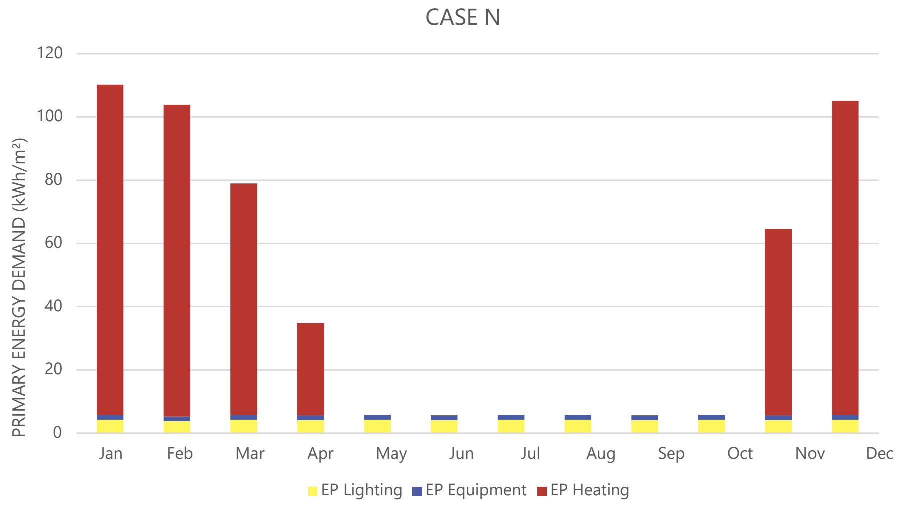


Figure 5.3.4.3- Primary Energy Uses in kWh/m2 per months (Case N)

Source: Author's elaboration

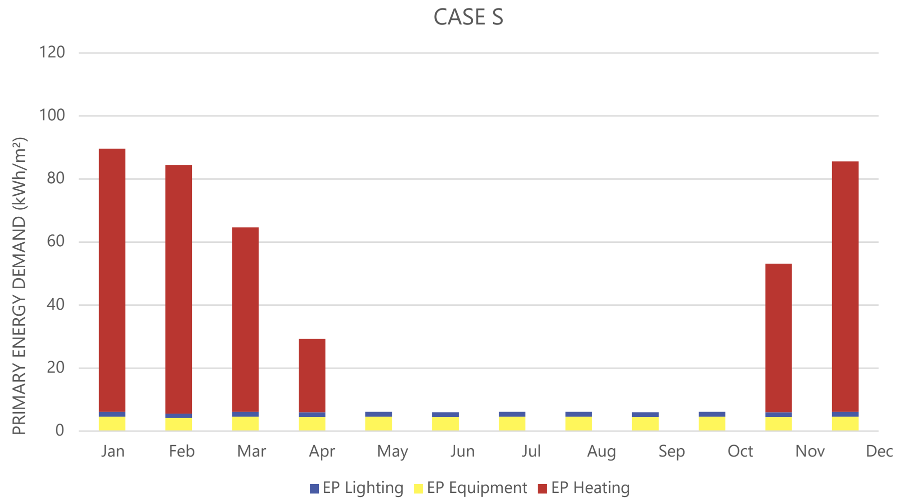


Figure 5.3.4.4 - Primary Energy Uses in kWh/m2 per months (Case S)

Source: Author's elaboration

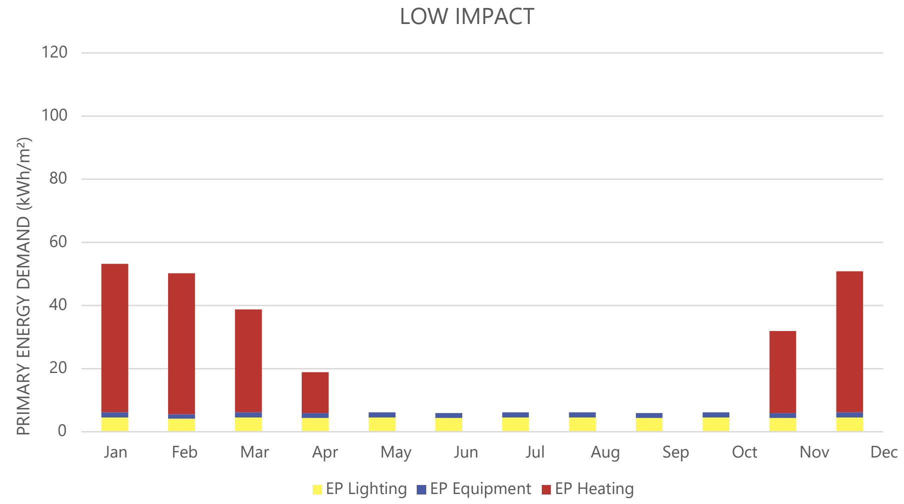


Figure 5.3.4.5 - Primary Energy Uses in kWh/m2 per months (Low Impact)

Source: Author's elaboration

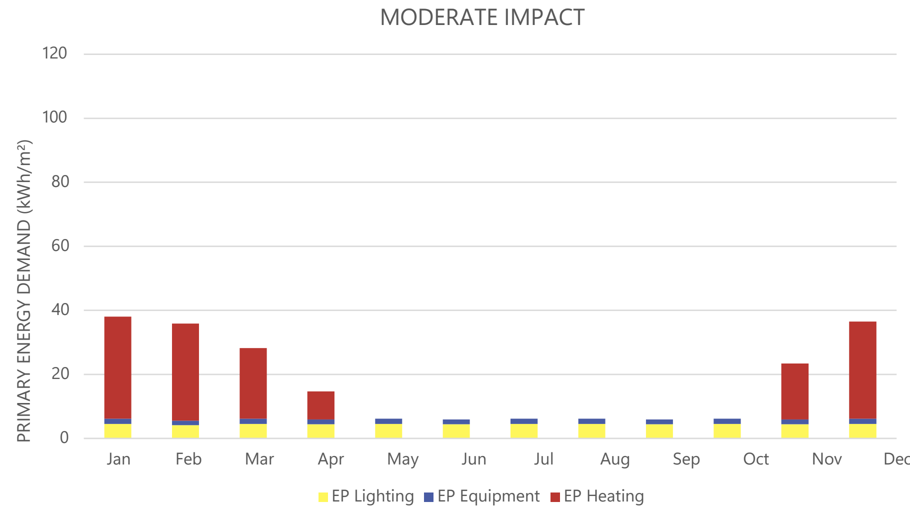


Figure 5.3.4.6 - Primary Energy Uses in kWh/m2 per months (Moderate Impact)

Source: Author's elaboration

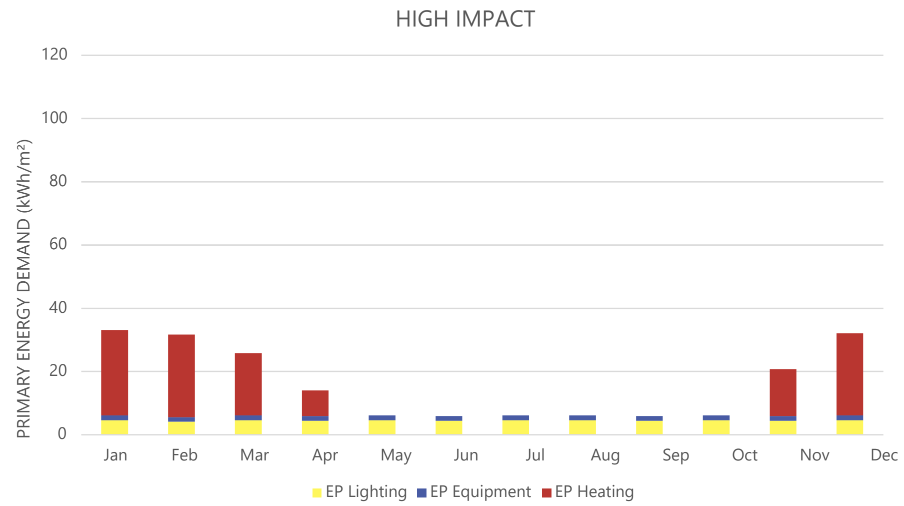


Figure 5.3.4.7 - Primary Energy Uses in kWh/m2 per months (High Impact)

Source: Author's elaboration

5.3.5 SOLAR POTENTIAL AND SAVINGS

To evaluate the photovoltaic potential of the house, the annual global Plane of Array (POA) irradiation on the roof was earlier simulated in section 4.1.4 considering 8 solar panels on the roof.

Since the south-facing roof has a high annual solar gain under local climatic conditions of around 2,195 kWh/m²/year, making it ideal for the PV installation. It receives more direct irradiation throughout the year, with a balanced exposure through both summer and winter. Although its yield is very close to the west roof, the latter is the main facade and entrance, and typically, it is advised that those installations don't remain visible on the main facade. Additionally, after calculating the PV Output with an efficiency of 20% and system losses of 14%, the south-facing roof is more favorable making it the first choice, yielding approximately 4,983 kWh per year, corresponding to 13.5 kWh/m²/year when normalized to the total conditioned floor area of the house (368.26 m²).

When integrated into the energy balance, the PV system reduces the delivered energy demand by up to 2.62% compared to the baseline scenario (Case N), and up to 83.8% in the most efficient retrofit scenario (High Impact). This shows that while the envelope improvements provide the largest share of savings, roof-mounted PV offers an additional measurable contribution to the energy reduction and cost savings.

For the cost analysis, the primary energy demand will only include lighting and equipment for both Case N and the low-impact bundle, since they are relying on wood as a heating source. Therefore the annual energy demand is lower (Figure 5.3.5.1).

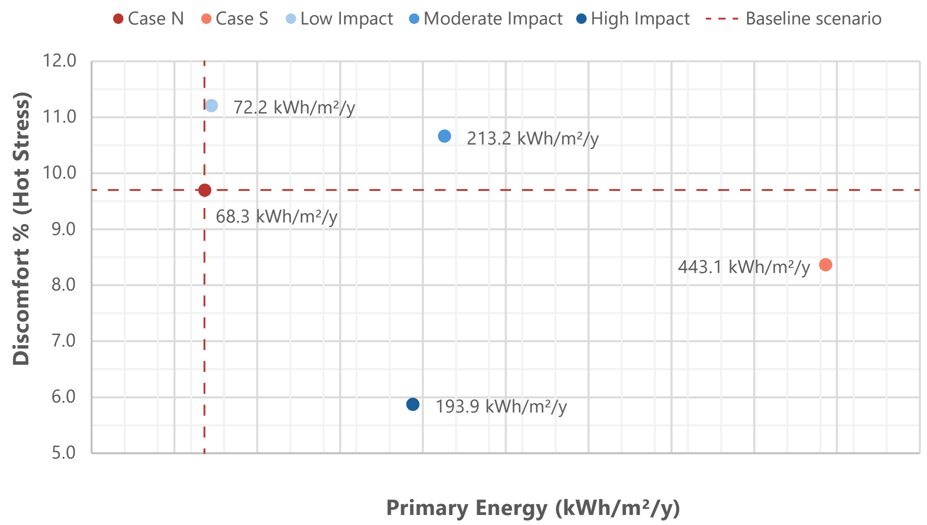


Figure 5.3.5.1 - Discomfort vs Adjusted Primary Energy

Source: Author's elaboration

Quantifying savings in $USD:

In order to obtain the cost analysis, it is crucial to convert the primary energy to delivered energy of the house. Consequently, Table 5.3.5.1 summarizes all the simulations results seen in Sections 4.4.4, 4.5.3, and 5.3.1-2-3, including their primary energy factors (PEF), and system efficiencies to determine the delivered energy use of the house. In addition, Table 5.3.4.2 illustrates the final delivered energy results in **kWh/m²/year** per case (excluding the heating for Case N, S and low-impact bundle), and for a **house area of 368.2 m²**.

Table 5.3.5.1 - Summarized Values for all Cases

Source: Author's elaboration

CASE		System Efficiency	PEF	Primary Energy (kWh/m²/y)	Delivered Energy (kWh/m²/y)	Total Delivered Energy (kWh/m²/y)	Hot Stress (%)
Case N	Lighting	1.00	1.97	50.05	25.41	34.67	9.7
	Equipment	1.00	1.97	18.26	9.27		
	Heating	0.54	1.00	463.66	-		
Case S	Lighting	1.00	1.97	50.05	25.41	34.67	8.4
	Equipment	1.00	1.97	18.26	9.27		
	Heating	0.54	1.00	370.96	-		
Low Impact	Lighting	1.00	1.97	50.05	25.41	34.67	11.2
	Equipment	1.00	1.97	18.26	9.27		
	Heating	0.85	1.00	270.99	-		
Moderate Impact	Lighting	1.00	1.97	50.05	25.41	106.25	10.7
	Equipment	1.00	1.97	18.26	9.27		
	Heating	1.93	1.97	140.99	71.57		
High Impact	Lighting	1.00	1.97	50.05	25.41	96.45	5.9
	Equipment	1.00	1.97	18.26	9.27		
	Heating	2.20	1.97	121.68	61.77		

Table 5.3.5.2 - Conversion of Delivered Energy

Source: Author's elaboration

CASE	Primary Energy (kWh/m²/y)	Delivered Energy (kWh/m²/y)	House Area (m²)	Annual Delivered Energy (kWh/y)
Case N	68.3	**34.7**	368.2	**12,776.5**
Case S	68.3	**34.7**		**12,776.5**
Low Impact	68.3	**34.7**		**12,776.5**
Moderate Impact	209.3	**106.3**		**39,139.7**
High Impact	190	**96.5**		**35,531.3**

We calculated in Section 4.1.4 the PV yield for 8 panels that is 4,983 kWh/year.

PV yield (8 panels) = 13.5 kWh/m²/year (normalized)

The energy split between the public grid EDL (58%) and diesel generators (42%) as seen in Figure 2.3.1.4, Section 2.3.1, is applied. In addition, photovoltaic production is assumed to offset demand proportionally between the grid and private generators, since the panels reduce the overall net demand.

In addition, Section 2.3.1 clarified the energy cost in Lebanon: for

1- Public grid: The first 100 kWh/month are at \$0.10, but above that its \$0.26 kWh/month in mountainous regions like Douma. Since consumption is much higher than 100 kWh, we assume that most PV offset the \$0.26/kWh portion.

2- Private generator: The tariff in mountainous zones is \$0.37/kWh.

To get our annual cost, we multiply the annual delivered energy by the tariffs, taking into account the ratio of public grid vs generator.

Annual Cost = DE x Tariff

Annual Cost Breakdown
Case N:
Grid (58%) = 7,410.4
Generator (42%) = 5,366.1

Case S:
Grid (58%) = 7,410.4
Generator (42%) = 5,366.1

Low Impact:
Grid (58%) = 7,410.4
Generator (42%) = 5,366.1

Moderate Impact:
Grid (58%) = 22,701
Generator (42%) = 16,438.7

High Impact:
Grid (58%) = 20,608.2
Generator (42%) = 14,923.1

Then, total savings are estimated for both the public grid and private generators as follows:

Using the delivered energy results (Table 5.3.5.2) and the 58% grid / 42% generator split (Figure 2.3.1.4), the grid's first 1,200 kWh per year is priced at \$0.10 then \$0.26/kWh, and the generator is priced at \$0.37/kWh (Section 2.3.1).

The PV offset = 4,983 kWh/y and applied proportionally (grid 2,890.1 kWh, generator 2,092.9kWh).

On the grid side, the PV reduces the \$0.26/kWh tier first.

Table 5.3.5.3 - Final Delivered Energy, Annual Cost, and PV Savings by Case

Source: Author's elaboration

The savings are constant across cases because the PV output is fixed at 4,983 kWh/yr and is split proportionally (58%/42%).

Each case has large grid consumption above the first 1,200 kWh/yr, so grid savings fall always in the 0.26 × 2,890.14 = \$751.44, and generator savings are 0.37 × 2,092.86 = \$774.36

The total of savings in \$USD is \$1,525.79 per year, but the % savings vary for each case since the baseline cost differs.

In Table 5.3.5.3, Case N, S and low-impact exhibit the highest % of savings rates because their delivered energy is the lowest (heating excluded), so the same PV offset represents a larger share of their annual cost.

CASE	Annual Delivered Energy *(kWh/y)*	Total Annual Cost *(\$USD)*	PV offset *(kWh/y)*	% savings *(primary energy)*	\$ savings *Public Grid \$0.26/kWh*	\$ savings *Generator \$0.37/kWh*	Total \$ savings (Grid + Gen)
Case N	**12,776.5**	\$3,720.2		41%			
Case S	**12,776.5**	\$3,720.2		41%			
Low Impact	**12,776.5**	\$3,720.2	4,983	41%	\$751.4	\$774.4	\$1,525.8
Moderate Impact	**39,139.7**	\$11,792.6		12.9%			
High Impact	**35,531.3**	\$10,687.7		14.3%			

06 CONCLUSION

Conclusion

The hypothesis of Section 3.2 is only partially confirmed: while enhancing passive strategies of the house provides noticeable improvements, it remains insufficient on its own. Active system upgrades ultimately make the most significant difference in comfort and energy performance.

Douma's solar potential highlights that relying on PV grids, whether private or public, offers a valuable pathway for resilient energy supply.

When comparing low-, moderate-, and high-impact bundles, the differences in energy consumption are not drastic at first glance. However, since the low-impact bundle depends on wood as a fuel similarly to Case N, its energy contribution is not fully counted — if included, the total consumption is the highest (Figures 5.3.4.1 and 5.3.4.3). On a delivered energy basis, both Case N and low-impact exhibit the highest percentage of savings from PV precisely because their delivered energy is the lowest (heating excluded). The same PV system provides a consistent annual saving of $1,526 at current tariffs (2024-2025), with savings split in proportion to the established 58% EDL (public grid) and 42% generator supply. Costs are calculated on delivered energy that is converted from the primary energy via the applied PEF.

Thus, the moderate impact bundle emerges as the most balanced solution. By combining traditional and modern heating systems with medium-range efficiencies, it offers a realistic refurbishment option that balances comfort, energy consumption, and cultural identity preservation.

This study can be expanded into a practical guideline for the refurbishment of traditional Lebanese houses, and by extension, for heritage buildings in similar Mediterranean contexts. Its strength lies in combining energy simulation, comfort assessment, and heritage preservation criteria into a step-by-step framework that is adaptable to different building types and climates.

The approach begins by establishing a baseline adaptive case (Case A) that isolates the passive performance of the existing envelope and its vernacular features. This is followed by the baseline refurbished case with active systems (Case N), which reflects the most common current practices and highlights the gap between traditional performance and contemporary comfort needs. Then, the regulation-compliant retrofit (Case S) allows for benchmarking against available standards, even when such standards are not directly tailored to vernacular contexts, as in Lebanon.

The second stage introduces a sensitivity analysis, using a one-at-a-time (OAT) approach to quantify the relative influence of each variable (e.g., wall U-value, glazing g-value, system efficiency, infiltration rate, lighting density). By normalizing and grouping results, the analysis identifies which interventions have the highest impact on energy use and thermal comfort, thereby supporting evidence-based prioritization.

Finally, the methodology consolidates individual interventions into impact bundles (low, moderate, high), which represent coherent retrofit scenarios with different balances between performance and heritage compatibility. These bundles are tested as whole-house scenarios and compared against the baseline cases, giving us clear insights into trade-offs between energy savings, comfort gains, and preservation of cultural value.

This three-step process - (1) baseline and standard cases, (2) sensitivity analysis, and (3) consolidated bundles - form a replicable guideline. It allows practitioners, policymakers, and homeowners to evaluate refurbishment options systematically, even in the absence of national standards. Importantly, it also ensures that retrofit decisions are not only driven by technical efficiency, but also by the degree of impact on the traditional character.

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