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Decarbonization, robustness and resilience: the challenges of future buildings

The Dammusi of Pantelleria Island, a case study

Supervisor
Stefano Paolo Corgnati

Co-supervisors
Cristina Becchio
Sara Viazzo
Giulia Crespi

Candidate
Sonia Scanavino
s286552

To my family, for always loving and supporting me.

To my teammates, as well as friends, who made this five years adventure unforgettable.

To my friends, for being by my side.

To God, who is the cause of my desires and of my acts.

To myself, because I have always believed.

Summary

Nowadays, climate change is the most debated issue since it is an inevitable consequence of mankind's actions. Due to their relevant energy and environmental impact, buildings are recognized among the main causes of climate change. According to the Global Status Report for Buildings and Construction, buildings account for 36% of global energy demand and 37% of energy-related CO_2 emissions. Consequently, buildings must undertake the decarbonization process, which is one of the most decisive solutions to curb, to achieve the sector transition, which will be guided by higher electrification of end-uses and deployment of renewable energy sources.

Furthermore, future buildings performance, in terms of energy needs and occupants' comfort and well-being, will inevitably be affected by a wide range of foreseeable and unforeseeable events during the operational phase (e.g., energy supply interruptions, external air temperature increase, natural events, occupants' habits, etc.). Therefore, the design of new constructions and the retrofit of existing buildings cannot be performed with the sole objective of achieving high energy performances, but it asks for the introduction of features capable of increasing buildings robustness and resilience to deal with a wide range of elements that can impact on their operations and performances. In detail, robustness concerns the insensitivity of some parameters to uncertainty, while resilience focuses on withstanding adversity and recovering from it. These definitions can be tuned for buildings, opening the discussion on the possible strategies capable of increasing their resilience and/or robustness. To better tailor these concepts at building level, the work aims to collect and clarify the definitions and implications of these concepts for the built environment, since they are often interchanged or used as synonyms.

Therefore, decarbonization, robustness and resilience are the main challenges of future buildings, which especially need to be addressed by existing buildings, which represent most of the stock.

In this frame, the thesis focuses on Pantelleria Island, which is an interesting reality to be deepened. On the one hand, Pantelleria Island, which is one of the three Italian islands selected by the Clean Energy for EU Islands Secretariat as leading islands for energy transition process, represents a key context for innovative energy interventions. On the other hand, the Pantelleria Island existing building stock, which is characterized by traditional and mainly historic buildings, the *dammusi*, must deal with existing limitations and constraints on energy interventions, making the challenges even more complex. Pantelleria Island, indeed, is not interconnected to the national power grid and largely depends for its energy supply from diesel systems. According to the *Agenda per la Transizione Energetica* of the Pantelleria Island, its residential sector accounts for 38%

of electricity consumption, with a self-sufficiency level of only 1%. Therefore, the improvement of its energy performances and the exploitation of renewable sources for its energy supply are identified as key actions for Pantelleria Island decarbonization process.

In addition, Sicily, and thus Pantelleria, is already and will be one of the most severely European regions affected by the increase of external temperatures in summer, as a consequence of climate change and global warming issues, affecting the building sector and tourism, which is one of the main economic resources of the island.

In line with the above, the thesis aims to investigate possible retrofit solutions for the existing residential building stock of Pantelleria Island, aiming to increase both its energy efficiency and its robustness and resilience to potential future stresses. In detail, three archetypes of *dammusi* are defined, based on available information on Pantelleria buildings, to be representative of the existing stock, and their energy models in the current state are simulated using Edilclima software. After analyzing the current energy needs and consumptions of the *dammusi* archetypes, alternative strategies of energy retrofit are identified, in line with the existing regulatory constraints for the protection of the historical and architectural heritage of the island. Through energy simulations, retrofit scenarios are compared, exploring their capability in reducing the environmental impact of the *dammusi* and in improving the *dammusi* robustness and resilience to future uncertainties, dependent on climate change consequences or energy supply interruptions. Scenarios results prove that the implementation of a set of retrofit solutions at building scale can provide remarkable cuts of consumptions and emissions, meeting decarbonization targets. The same retrofit solutions, however, often enhance also *dammusi* buildings resilience and robustness, making *dammusi* prepared against future uncertain and inevitable occurrences.

Sommario

Oggigiorno, il cambiamento climatico è la tematica più dibattuta, essendo l'inevitabile conseguenza delle azioni dell'umanità. A causa del loro rilevante impatto energetico ed ambientale, gli edifici sono considerati tra le principali cause del cambiamento climatico. Secondo quanto riportato dal *Global Status Report for Buildings and Construction*, gli edifici rappresentano il 36% del consumo globale di energia e il 37% delle relative emissioni di CO_2. Per questo motivo, è fondamentale che gli edifici intraprendano la strada della decarbonizzazione per raggiungere la transizione energetica del settore edilizio, guidata dalla maggiore elettrificazione degli usi finali e dallo sfruttamento delle fonti di energia rinnovabili.

Inoltre, soprattutto durante la fase di utilizzo, gli edifici possono essere soggetti ad una serie di eventi, prevedibili e non, che possono avere un impatto significativo sulle loro prestazioni energetiche, in termini di consumi energetici e di comfort degli occupanti (e.g., interruzioni delle forniture energetiche, aumento delle temperature esterne, eventi naturali, abitudini degli occupanti, ecc.). La progettazione di nuovi edifici e la riqualificazione di quelli esistenti, quindi, non può ambire soltanto al raggiungimento di un'elevata prestazione energetica, ma deve rendere gli edifici robusti e resilienti, ovvero in grado di far fronte a una vasta gamma di eventi incerti. In particolare, se la robustezza riguarda l'insensibilità di alcuni parametri rispetto a un'incertezza prevedibile, la resilienza si focalizza sulla capacità di resistere a un evento avverso improvviso e di riprendersi da esso. Queste definizioni possono essere adattate agli edifici, aprendo una discussione riguardo le possibili strategie in grado di aumentare la loro resilienza e/o robustezza. Dal momento che i termini di "robustezza" e "resilienza" sono spesso intercambiati e usati come sinonimi, la prima parte della tesi cerca di chiarire il significato che questi due termini assumono nell'ambito energetico e edilizio, fornendo una serie di definizioni e interpretazioni che derivano dalla letteratura specifica.

La decarbonizzazione, la robustezza e la resilienza, quindi, rappresentano le principali sfide degli edifici del futuro, che dovranno essere affrontate soprattutto da quelli esistenti, che rappresentano la porzione più consistente del patrimonio edilizio.

In questo contesto, la tesi si concentra sull'isola di Pantelleria, che rappresenta sicuramente una realtà interessante da approfondire. Infatti, è una delle tre isole italiane selezionate come isola-pilota per la transizione energetica dell'iniziativa *Clean Energy for EU Islands*, rappresentando un contesto chiave per la sperimentazione di interventi energetici innovativi. Inoltre, il patrimonio architettonico esistente dell'isola, costituito dalle tipiche abitazioni locali, i dammusi, è sottoposto a diversi vincoli normativi che possono limitare gli interventi energetici su di essi, rendendo le sfide

ancora più complesse. L'isola di Pantelleria, infatti, non è interconnessa alla rete elettrica nazionale e il suo approvvigionamento di energia dipende in gran parte da combustibili fossili. L'Agenda per la Transizione Energetica dell'isola di Pantelleria riporta che il settore residenziale rappresenta il 38% dei consumi di energia elettrica e presenta un livello di auto-sufficienza energetica pari all'1%. Il miglioramento delle prestazioni energetiche del settore residenziale e il maggior impiego di fonti di energia rinnovabile, quindi, costituiscono azioni-chiave all'interno del processo di decarbonizzazione dell'isola di Pantelleria.
Inoltre, la Sicilia, e, dunque, Pantelleria, sarà una delle regioni che vedranno un maggior aumento delle temperature esterne, specialmente nella stagione estiva, come conseguenza del cambiamento climatico e del riscaldamento globale. Questo fenomeno può andare a incidere sul comportamento degli edifici e sul turismo, che costituisce una delle principali risorse economiche dell'isola.

In linea con quanto detto finora, la tesi vuole identificare possibili soluzioni di retrofit per il patrimonio residenziale dell'isola, al fine di rispondere alle sfide di decarbonizzazione, resilienza e robustezza. A partire dall'analisi del patrimonio architettonico di Pantelleria, sono stati individuati tre archetipi di *dammuso*; ogni archetipo è rappresentativo di una porzione del patrimonio edilizio. Attraverso l'utilizzo del software Edilclima, i modelli energetici dei tre archetipi sono stati costruiti e simulati. Dopo aver valutato la prestazione energetica nel loro attuale stato di fatto, in termini di consumi ed emissioni, sono state definite diverse soluzioni di retrofit, in linea con i vincoli normativi vigenti. Gli scenari di retrofit sono confrontati al fine di analizzare la loro efficacia nel ridurre gli impatti ambientali dei dammusi e nel migliorarne la robustezza e la resilienza rispetto alle conseguenze del cambiamento climatico o a improvvise interruzioni dell'approvvigionamento di energia. I risultati degli scenari dimostrano che l'implementazione di diverse soluzioni di retrofit a livello di stock può permettere di ottenere notevoli riduzioni di consumi energetici ed emissioni, avvicinandosi agli obiettivi di decarbonizzazione; le stesse soluzioni di retrofit, inoltre, possono aiutare a migliorare la robustezza e la resilienza dei dammusi per rispondere agli incerti e inevitabili eventi futuri.

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1. Introduction

Humanity's dependance on fossil fuels since the industrial revolution has strongly contributed to climate change. Human activities of the last century and a half have triggered the so-called anthropogenic greenhouse effect, which is the result of carbon dioxide and other greenhouse gases emissions (GHG) into the atmosphere (EGP, 2022). According to Intergovernmental Panel on Climate Change (IPCC), the anthropogenic greenhouse effect is the main cause of global warming. The rising temperatures of the planet and the increase of the frequency of extreme weather events are evident phenomena of climate change. Therefore, climate change is the most widely discussed issue. At COP 26 [1] in November 2021, nations reaffirmed the commitment, already made with the Paris Agreement [2], to limit global warming to below 2°C and aim for 1.5°C (UNFCCC, 2021). To achieve this, all states are called up to cut carbon emissions, reaching net zero emissions target by the middle of the century.

In this frame, buildings sector is strongly involved. According to Global Status Report for Buildings and Construction, buildings account for 36% of global energy demand and 37% of energy related CO_2 emissions (UNEP, 2021). Therefore, immediately and significantly reducing GHG from the buildings sector is critical for reaching the Paris Agreement goals: *"By 2030, the built environment should halve its emissions, whereby 100% of new buildings must be net-zero carbon in operation, with widespread energy efficiency retrofit of existing assets well underway, and embodied carbon must be reduced by at least 40%, with leading projects achieving at least 50% reductions in embodied carbon. By 2050, at the latest, all new and existing assets must be net zero across the whole life cycle, including operational and embodied emissions"* [3](UNEP, 2021).

To better outline the meaning of the "net-zero buildings" mentioned above, some definitions [4] are listed:

- *"Net-zero operational energy buildings are buildings whose energy consumption over the course of the year is offset by renewable energy generation*" (UNEP, 2021);

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[1] COP stands for Conference of the Parties. Parties (196 countries and Europe) are the signatories of the United Nations Framework Convention on Climate Change (UNFCCC), which is a treaty agreed in 1994. The treaty envisages annual international conferences on climate change, the Conferences of Parties (COP) (UNFCCC, 2021).

[2] The Paris Agreement was agreed at COP21 in 2015 (UNFCCC, 2021).

[3] The goal was set by the United Nations Framework Convention on Climate Change's Marrakech Partnership for Global Climate Action Human Settlements Pathway, co-led by GlobalABC. It was also adopted by the #BuildingToCOP26 Coalition (UNEP, 2021).

[4] The definitions, provided in *Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector,* p. 25, (UNEP, 2021) are based on those described in *Zero energy building definitions and policy activity: An international review,* OECD/IPEEC, 2018

- *"Net-zero operational carbon buildings are buildings whose carbon emissions resulting from electricity consumption and any other fuels consumed on-site are offset through renewable energy generation or other forms of carbon offsetting"* (UNEP, 2021)*;*
- *"Whole-life net-zero carbon emissions buildings are buildings whose carbon emissions from the materials used in their construction, or embodied carbon, are offset, as well as their operational carbon emissions"* (UNEP, 2021)*;*

In addition, the term "net-zero" can also refer to a building which energy demand is close to zero. These definitions highlight the great work required to make buildings efficient, especially the existing buildings, which represents most of the stock.

In Europe, today, the energy renovation of the existing building stock is a central theme since buildings are responsible for 40% of energy consumption and 36% of greenhouse gases emissions in the European Union (EC, 2020). Making buildings more efficient is the aim of one of the European legislative initiatives included in the Clean Energy for all European Package adopted in 2019 to decarbonize European energy system in keeping with the European Green Deal [5] objectives. Clean Energy for all European Package consists of eight new laws that European countries have to convert into national laws (EC, 2019b). Among them are the *Energy Performance of Buildings Directive* (EU 2018/844) that sets out existing buildings renovation strategy (EC, 2018b) and the Renewable Energy Directive (EU 2018/2001) which focuses on the introduction of renewable energy sources in the European energy mix for a share of 32% by 2030 (EC, 2018b).

In addition to legislative initiatives, the European Commission published the Renovation Wave strategy in 2020 regarding buildings energy efficiency and sector decarbonization commitment. This strategy identifies three focus areas (EC, 2020):

- Tackling energy poverty and worst-performing buildings;
- Public buildings and social infrastructure;
- Decarbonizing heating and cooling.

As regard the third mentioned point, space heating and space cooling in buildings are actually mainly provided by the fossil fuels combustion, such as natural gas and oil, which are the main energy source. Building decarbonization, which is "*the process of reducing or eliminating the emissions that contribute to climate change from building energy sources"* (Elevate, 2022), is characterized by:

1. Building energy efficiency, namely the reduction of building energy needs by improving building envelope energy performance;

[5] The European Green Deal is a set of transformative policies agreed by European Commission in 2019 to lead Europe to reduce net greenhouse gas emissions by at least 55% by 2030 and to achieve climate neutrality by 2050 (EC, 2019a).

2. Building electrification, that is the replacement of energy systems that employ fossil fuels with electric energy systems;
3. Use of renewable sources. On-site renewable sources can generate electricity used to meet building electricity consumptions. This reduces the electricity share taken form the grid, which still can come from fossil fuels, like coal;
4. Management of electricity loads, namely the shifting of energy loads to different times of the day in order optimize the use of renewable energy generated from renewable sources and reduce the impact on the grid. In this respect, electric storage can also be taken into account.

To facilitate and accelerate the processes of buildings energy renovation and decarbonization, many research and innovation projects are supported and funded by the European Commission through the Horizon Europe research programme (EC, 2021). The building sector goals, commitments and legislative initiatives outlined so far fall within the European Climate Mitigation Strategy, which means "*making the impacts of climate change less severe by preventing or reducing the emission of greenhouse gases into the atmosphere"* (EEA, 2022a).

However, climate change will inevitably affect future buildings performance, in terms of energy needs, as well as occupants' comfort and well-being. Indeed, the high energy performance building of today will have to cope with a different context in the future. On the one hand, buildings future energy consumptions will be greatly vulnerable to global warming, due to the dependency of heating and cooling energy demands from external variables, considering both the environmental parameters, such as rising external temperatures, and the varying occupants' requests. This relates to robustness concept, which concerns the insensitivity of some parameters to foreseeable uncertainty.

On the other hand, in the last few years various unexpected events have occurred, whose consequences also affect the building sector. In 2019, COVID-19 pandemic has significantly affected people behavior, whose stay-at-home living patters resulted in different energy consumption of residential buildings (Chinthavali et al., 2022). In 2022, Russia's invasion of Ukraine caused a disruption in the global energy market. Europe largely depend on Russian fossil fuels, and this is used as an economic and political instrument (EC, 2022). The European Commission presented the REPowerEU Plan [6] to tackle this situation. Therefore, it is not to be excluded that Europe suddenly finds itself out of natural gas, which is the leading energy source for residential heating in the EU, with a share of 39% in 2019 (Enerdata, 2022). Added to these two major events, the

[6] REPowerEU provides for measures to reduce energy dependency on Russia *"through energy savings, diversification of energy supplies, and accelerated roll-out of renewable energy to replace fossil fuels in homes, industry and power generation"* (EC, 2022).

increasing frequency of unforeseeable natural events, such as floods, heat waves and earthquakes, is threatening buildings and inhabitants, which will be more and more affected from now on. Consequently, resilience concept is required, term that focuses on withstanding unexpected adversities and recovering from them.

Therefore, these last themes relate to European Climate Adaption Strategy, which means "*anticipating the adverse effects of climate change and taking appropriate action to prevent or minimize the damage they can cause or taking advantage of opportunities that may arise"* (EEA, 2022a); Adaption Strategy is then complementary to Mitigation Strategy.

Based on the above, the design of new constructions and the retrofit of existing buildings cannot be performed with the sole objective of achieving high energy performances, but it asks for the introduction of features capable of increasing buildings robustness and resilience to deal with a wide range of elements that can impact on their operations and performances.

Currently, despite their importance, adaption measures concerning buildings robustness and resilience are not embedded into country energy codes and legislations, which focuses only on mitigation measures pursuing buildings decarbonization and energy efficiency.

However, it would be desirable to combine the reduction of buildings impact on climate with the investment in adaptation and resilience measures in order to better deal with the uncertainties of the future. As a consequence, the thesis deals with the description of the main challenges for the buildings of the future, which will need to achieve the main goals of sustainability (decarbonization), robustness and resilience, with a view to both mitigation and adaption strategies. These challenges appear even more urgent for existing buildings, which represent most of the European stock (EEA, 2022b) and which energy conditions are still poor. This consideration is particularly relevant for Italy, which stock is also characterized by the presence of buildings with great historic and architectural value, entailing further limitations and constraints on the possible interventions that could be undertaken to improve their energy conditions and to increase their sustainability, robustness and resilience levels.

The thesis perfectly fits with this framework, focusing on a particular context, represented by the Pantelleria Island (in Sicily). The island is characterized by the presence of typical residential buildings, named *dammusi*. Despite their poor energy conditions, *dammusi* buildings are subjected to architectonic and landscape constraints, which limit the possible interventions that could be undertaken to retrofit them based on the previously defined goals (i.e., sustainability, robustness, resilience). Starting from the identification of three archetypes of *dammusi*, based on the reference building approach, to represent the existing stock of Pantelleria Island, the thesis aims first to study their current performance in energy and environmental terms, by defining a set of performance indicators; moreover, attention is focused on the definition and simulation of possible retrofit solutions, which are identified as mitigation and adaptation measures at the same time, aiming to both increase their energy performance in the view of decarbonization and to improve robustness and resilience to stand potential future stresses impacting on their operations.

The thesis is organized as follows; Chapter 2 presents the results of a literature review regarding the concepts of robustness and resilience for the built environment, analyzing their main definitions, features, and assessment methods; the review aims to identify possible strategies capable of enhancing the robustness and resilience of buildings, to guide the design/retrofit phase according to these goals. Chapter 3 describes the methodological steps developed for the work. Chapter 4 introduces the case study of the thesis, providing some information for the current energy situation of Pantelleria Island, while Chapter 5 reports the details of the application of the methodological approach to the Pantelleria Island building stock, and specifically to its typical *dammusi* buildings, and summarizes the main results achieved. Finally, conclusions and future perspectives of the work are reported in Chapter 6.

The graphical representation of the thesis workflow is shown in Figure 1 and tries to highlight the main logical connections among the thesis topics, referring to all thesis Chapter, from introduction to conclusions, tied by the core section referred to methodology. Each Chapter tries to answer some question in order to outline the main points deepened in each section.

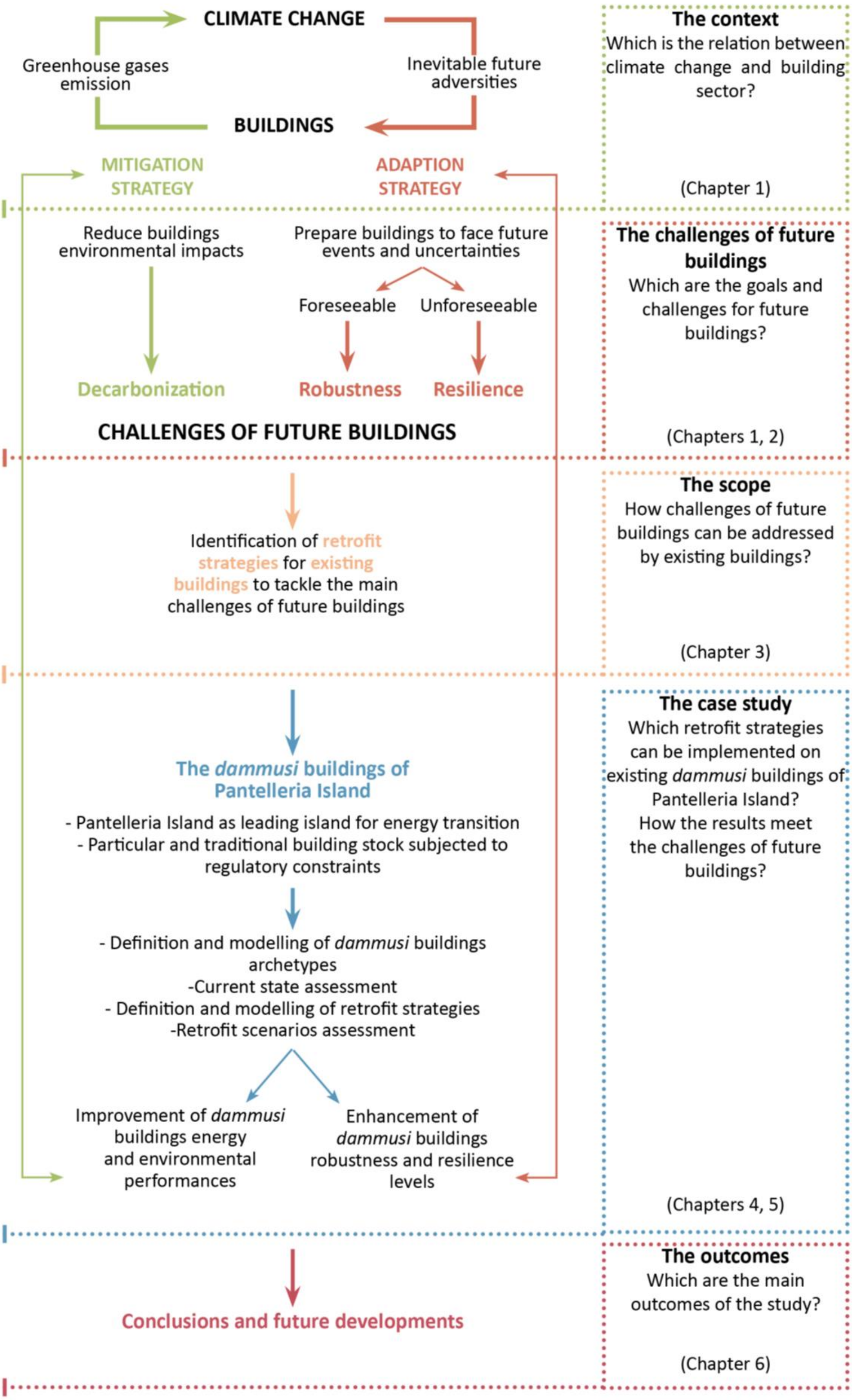


Figure 1. Roadmap of the thesis workflow.

2. Robustness and resilience in the built environment: new challenges for future buildings

Until now, the design of new constructions and the retrofit of existing buildings has been mainly performed with the objective of achieving high energy performances in order to reduce energy consumptions and greenhouse gases emissions. Nevertheless, the only evaluation of buildings performance excludes the potential effects due to different types of uncertainties, among which it is possible to cite occupants' behavior and/or climate change phenomena, which may impact on buildings operations and cause a discrepancy between designed and actual buildings performances (Homaei et al., 2020). In order to deal with these uncertainties, the introduction of robustness and resilience properties is required (Moazami et al., 2019a). The concepts of robustness and resilience are borrowed from other disciplines and then transferred to the built environment, where they are often interchanged or used as synonyms and a limited number of definitions are provided.

In general, robustness and resilience concepts are differently defined in the built environment according to the following three characteristics (Attia et al., 2021):

1. Scale: scale of the system analyzed (e.g., city, district, neighborhood, building, etc.);
2. Type of uncertainty: foreseeable (e.g., occupant behavior, climate change effects, decarbonization) or unforeseeable (e.g., natural disruptive events, power outages, pandemics or geopolitical changes);
3. Time: time frame for disturbance and its assessment (days, months, year, decades, etc.).

The present work focuses on robustness and resilience concepts at a building scale, differentiating them according to the type of uncertainty and time frame. In particular, robustness concerns the insensitivity of some parameters to uncertainty, while resilience focuses on withstanding adversity and recovering from it. At a building level, robustness is often related to the building performance, which is assessed over a longer time frame, such as a year. Moreover, uncertainties affecting robustness are always foreseeable and are mostly related to:

- Occupants' behavior (different lifestyles and preferences);
- Climate change effects (growing external temperatures or different solar radiation);
- Decarbonization (variable renewable energy sources integration in the energy mix).

Given the above, a building can be defined robust if it is able to maintain its expected performance, despite uncertainties affecting it (Homaei et al., 2020).

As regard resilience in the built environment, however, it usually has to do with buildings thermal resilience or buildings energy supply resilience. Uncertainties affecting resilience are always unforeseeable events including:

- Natural time-focused disruptive events (floods, earthquakes, hurricanes, heat waves, etc.);
- Power outages (common occurrences caused by previously cited natural events or due to power grids intermittency);
- Pandemics (unexpected situation that led to changes in buildings use);
- Geopolitical changes (sudden changes that may cause deficiencies and malfunctions in buildings energy supply).

Currently, at a building level, resilience is often evaluated with regard to natural disruptive events or against power outages with particular attention to building energy systems. That is why, differently from robustness assessment, resilience is evaluated over a shorter time frame, such as some days. In fact, since a building is defined as resilient if it is able to maintain its services always available to occupants (Hewitt et al, 2019), resilience assessment is made by considering building behavior against time-focused adversity before, during and after the disruptive event (Homaei et al., 2021).
Starting from this general overview, robustness and resilience themes are further deepened in the next paragraph by referring to the existing literature.

2.1 Literature review

The literature about robustness and resilience collected in this paragraph focuses on applications and definitions at building scale. Table 1 and Table 2 provide a list of some studies about robustness and resilience, classifying them according to the investigated source of uncertainty, in line with the differentiation previously described. Table 3 report two review papers that focus on both robustness and resilience concepts, providing different definitions and interpretations.

Table 1. Studies about robustness in the context of the built environment

Robustness		
Reference	***Source of foreseeable uncertainty***	***Aim of the study***
Hoes et al., 2009	Occupants' behavior	Evaluate the effect of user behavior on building performance to assess requirements for design solutions to arrive at robust buildings.
Fabi et al., 2013	Occupants' behavior	Investigate how occupants' behavior varies according to the building envelope design.
Buso et al., 2015	Occupants' behavior	Investigate how alternating occupant behavior patterns impact the performance of different envelope design solutions.
Ferrara et al., 2017	-Climate change (i.e., weather conditions)	Study the *resilience/robustness** of a NZEB design to the variations of the boundary conditions in which the cost optimal calculation is performed.
Ascione et al., 2017	Climate change (i.e., weather conditions)	Evaluate robust cost-optimal energy retrofit solutions.
Kotireddy et al., 2018	- Occupants' behavior - Climate change (i.e., weather conditions)	Assess robustness of designs considering multiple performance criteria under uncertainties arising from the building's operation and from external factors.
Rouleau et al., 2019	Occupants' behavior	Evaluate the energy performance robustness of a dwelling to OB in terms of energy consumption and thermal comfort.
Moazami et al., 2019b	Climate change (i.e., weather conditions)	Evaluate the energy robustness of newly built and existing older buildings under the disturbance of mutable climate variables.
Homaei et al., 2020	- Occupants' behavior - Climate change (i.e., weather conditions)	Evaluate the performance robustness considering the diverse uncertainties in building operations and external factors.
Coppitters et al., 2021	- Occupants' behavior - Decarbonization	Evaluate the performance of residential building systems providing the least-sensitive designs to natural variability and effective actions.
Walker et al., 2022	-Occupants' behavior -Climate change (i.e., weather conditions) -Electricity grid decarbonization	Evaluate the building greenhouse gas emission performance considering future uncertain developments.
Ascione et al., 2022	Climate change (i.e., weather conditions)	Evaluate the *resilience/robustness** of buildings designed to be NZEB in term of energy balance.

*Despite the study discussion refers to resilience, it should be referred to robustness according to the classification previously described.

Table 2. Studies about resilience in the context of the built environment

Resilience		
Reference	***Source of unforeseeable uncertainty***	***Aim of the study***
Baniassadia et al., 2018	Power failure	Investigate the performance of high-rise residential apartment buildings under a three-day power outage scenario coinciding with a three-day heat wave.
Moshlei et al., 2018	Different failures (i.e., electric power grid failure or natural gas distribution grid failure)	Analyze systems resilience to potential internal and external failures.
Hewitt et al., 2019	Natural disruptive event (i.e., hurricane)	Question the relevance of green building features to support resilience during a disruptive event.
Sun et al., 2020	Natural disruptive event (i.e., hurricane)	Quantify how passive and active energy efficiency measures can improve thermal resilience to reduce heat-exposure risk.
Liu et al., 2020	Power failure	Evaluate the impact of energy storage systems for health care centers facing power failure during the pandemic.
Homaei et al., 2021	Power failure	Evaluate thermal resilience concerning building characteristics and occupancy during and after the disruptive event during heating season.
Yang et al., 2021	Power failure	Propose a resilient home energy management strategy to enable residential houses to implement self-power supply during a grid outage period.
Wang et al., 2022	Pandemics	Assess the possibility to leverage photovoltaic rooftop to supplement increased energy demand to safeguard energy resilience.
Hasselqvist et al., 2022	Power failure	Suggest a definition of household energy resilience that can be used to explore how households can ensure a good life in a future with variable availability of electricity.

Table 3. Studies about robustness and resilience in the context of the built environment

Robustness and resilience	
Reference	***Aim of the study***
Moazami et al., 2019a	Review the concepts of robustness and resilience and organize them into a framework that clarifies their relationships in the protection of buildings against climate uncertainties.
Attia et al., 2021	Review the existing resilience definitions and approaches defining a set of criteria: vulnerability, resistance, robustness, and recoverability.

Starting from the information collected so far, the following paragraphs specifically deal with robustness and resilience topics reporting definitions and assessment methods and indicators.

2.2 Focus on robustness: definitions, features and assessment

The first definition of robustness was introduced in the industry field by Taguchi in the 1940s. Taguchi defined robustness as *"the state where the technology, product, or process performance is minimally sensitive to factors causing variability (either in the manufacturing or user's environment) and aging at the lowest unit manufacturing cost"* (Taguchi et al., 2000). That is to say, *"a product or process is said to be robust when it is insensitive to the effect of source of variability, even though the sources themselves have not been eliminated"* (Fowlkes et al., 1995).

Thus, starting from the key concept of robustness, which is the insensitivity to uncertainties, several definitions have been provided in literature within the built environment, including the following:

1. *"Robustness is defined as the sensitivity of identified performance indicators of a building design for errors in the design assumptions"* (Hoes et al., 2009);
2. *"Performance robustness is defined as the ability of a building to maintain the preferred performance under uncertainties arising from the building operation and from external conditions"* (Kotireddy et al., 2018);
3. *"Robustness is the capability of keeping relative high performance in all possible weather and working conditions or scenarios"* (Hangxin et al., 2019);
4. *"Robustness is defined as the ability of a building to perform effectively and remain within the acceptable margins under the majority of possible changes in internal and/or external environments"* (Homaei et al., 2020).

The above definitions highlight the relation between robustness and building performance, which can be affected by uncertainties, resulting in a gap between the expected performance in the design phase and the real one in the operational phase (Rouleau et al., 2019). The potential robustness of a building, therefore, is strongly linked to the initial design or renovation phase. The design process that aims to achieve a building which performance is the least sensitive to perturbations due to uncertainties is called robust design (Moazami et al., 2019a). Definitely, a robust building is *"a building that, while in operation, can provide its performance requirements with a minimum variation in a continuously changing environment"* (Moazami et al., 2019a).

Nevertheless, robust buildings perform with low sensitivity only under typical and foreseeable conditions, such as occupants' behavior or predictable climate change conditions, but cannot be considered as such in case of unforeseeable events (Moazami et al., 2019a).

Depending on the studies purposes and contexts, different robustness assessment methods can be employed. Homaei et al. (2020) describe possible ones, which can be divided into probabilistic and non-probabilistic approaches, which are not discussed in detail here, being out of the scope of the thesis. The authors, however, highlight that the scenario analysis is one of the most widely used method and it is often complemented by probabilistic approaches, such as mean and standard deviation based on Taguchi method[7], to compare scenarios results.

The definition of different scenarios allows to formulate alternative future conditions in order to consider the effects of various uncertainties (changes in occupants' behavior, in climate conditions or in economic factors) in a building energy performance (Homaei et al., 2020). Buildings performance results for each scenario can be expressed through different performance indicators, such as building demands, energy consumption, thermal comfort, emissions or cost. According to the probabilistic approach, the most robust scenarios are those which performance indicators shows the smallest variation (standard deviation) around the target performance (mean) (Homaei et al., 2020).

Figure 2 shows the probabilistic distributions of robust and non-robust designs results applied to buildings performance. Therefore, from design conditions, scenarios buildings performance results can show various mean values and different deviations from them. Once the performance target, namely the desired mean value, and the robustness margin, that is the maximum allowed deviation, are fixed, robust designs

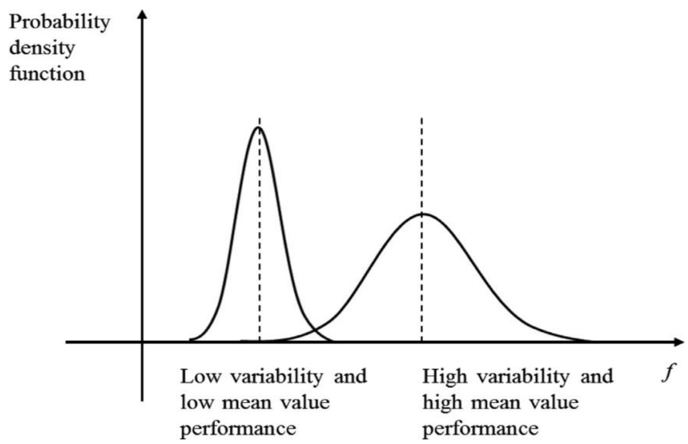


Figure 2. Probabilistic distributions of robust and non-robust designs results applied to buildings performance (Moazami et al., 2019b)

[7] It is also called Robust Design Method and it was used for the first time in product development in industry field (Homaei et al., 2020).

(scenarios) are those whose performance indicators results do not exceed robustness margins (Homaei et al., 2020).

Robustness assessment method is still not standardized and different approaches have been used and proposed in existing literature. Nevertheless, analyzing different studies, common parameters affecting robustness and similar performance indicators can be identified. Table 4 lists the main parameters affecting robustness, differentiated between building envelope, building systems and renewable energy sources. Moreover, Table 5 shows the main performance indicators mostly used in the literature to evaluate robustness, referring to energy, comfort, environmental and economic areas.

Table 4. Parameters affecting robustness

Parameters affecting robustness	
Building envelope	- Thermal mass - Window-to-wall ratio - Transmittance value - g-value of glazing - Wall solar absorptance - Roof solar absorptance - Overhang projection ratio - Infiltration flow rate - Material (embodied emissions)
Building systems	<u>Heating system:</u> - Type (electric, natural gas, GSHP, ASHP, pellets, etc.) - Generator efficiency - Efficiency loss of system - Flowrate - Inlet and outlet temperatures <u>DHW generation system:</u> - Hot water volume - Generator efficiency <u>Ventilation system:</u> - Average air change rate - Heat recovery efficiency - Electric efficiency <u>Lighting:</u> - Luminous efficacy
Renewable energy sources	<u>Photovoltaic system:</u> - PV capacity - PV system area - PV efficiency - PV performance ratio - PV orientation (azimuth/tilt angle) <u>Solar domestic hot water (DHW) system:</u> - Solar DHW system area <u>Heat pump:</u> - Heat pump capacity - Coefficient of performance (COP) <u>Thermal storage or battery capacity</u>

Table 5. Robustness performance indicators

Robustness performance indicators	
Energy performance	- Annual energy consumption [kWh/m^{2}y] - Energy consumption for heating [kWh/m^{2}y] - Energy consumption for cooling [kWh/m^{2}y] - Primary energy consumption [kWh/m^{2}y] - Total energy use [kWh/m^{2}y]
Comfort performance	- Number of unacceptable comfort level hours [h] - Operative temperature [°C]
Environmental performance	- Total GHG emissions [kg$_{CO2eq}$/m^{2}y] - CO_2 emissions [kg$_{CO2}$/y] - Life Cycle Environment Impact (LCEI): GHG emissions over the life cycle [kg$_{CO2eq}$/m^{2}y]
Economic performance	- Additional investments costs [k€] - Levelized Cost of exergy [€/MWh] - Life Cycle Cost (LCC) [€/m^{2}y] - Global costs [€/m^2] - Discount payback time [years]

In conclusion, robustness assessment can be considered as important as the performance evaluation during the design or the renovation phase (Homaei et al., 2020). The sensitivity of buildings performance to uncertainties during operational phase may be a cause of discrepancy between the actual future building performance and the expected one in design or renovation phase (Fabi et al., 2013). Therefore, taking into consideration robustness properties in the initial phase is fundamental to identify strategies capable of improving building robustness while guaranteeing high energy efficiency, resulting in a low performance deviation during the operational phase, despite possible uncertainties that may occur during its lifetime.

2.3 Focus on resilience: definitions, features and assessment

Resilience definitions are various and numerous, depending on the discipline. Resilience was initially defined in the ecological field as "*the ability of an ecosystem to rearrange its organization outside of its equilibrium state to another one when facing a perturbation"* (Holling, 1973). In other disciplines, such as engineering and economics, resilience is defined as "*the ability of a system to resist perturbations outside of its equilibrium state and its speed to come back to it"* (Holling, 1973; Martin et al., 2015).

The resilience concept, therefore, implies the key capacity of withstanding adversity and recovering from it. Consequently, the definition of resilience necessitates the occurrence of a shock (Attia et al., 2021). The following resilience definitions at a building scale have been found in literature:

1. *"Resilience is the capacity of a system to withstand and recover during and after the occurrence of an extreme event"* (Moazami et al. 2019a);
2. *"Resilience is defined in terms of the availability of services that a building is capable of maintaining under conditions of stress, and its ability to restore those services in order to continue operating" (Hewitt et al. 2019);*
3. *"Resilience refers to the ability of a building to prepare for, withstand, recover rapidly from, and adapt to major disruptions due to extreme weather conditions"* (Sun et al. 2020);
4. *"Resilience is the persistence or fulfilment of the entity function in the face of disturbances. In energy related resilience research, the energy system or the power system are taken as resilience entity and energy supply is the function to sustain" (*Hasselqvist et al., 2022).

Referring to the previous definitions, resilience at a building level seems usually defined as:

a. Thermal resilience, which reflects the impacts of extreme events on buildings occupants' comfort (Homaei et al. 2021);
b. Energy resilience, which regards buildings energy systems resilience, on which buildings activities depends (Hewitt et al., 2019).

Thermal and energy resilience are concepts that have been particularly deepened in literature until now. Homaei et al. (2021) highlight that resilience assessment approaches can be qualitative or quantitative. The quantitative approaches are further subdivided into structural-based and general modelling. The first approach takes into consideration system characteristics and behavior, while the latter does not. It is beyond the scope of this thesis to enter into the merits of the specific methods characteristics.

Studies about thermal resilience (Sun et al. 2020; Homaei et al., 2021) stress the importance of evaluating how passive and active energy efficiency measures can improve thermal resilience during building design or retrofit, in order to ensure occupant thermal comfort even in case of extreme occurrences. In detail, thermal resilience focuses on building thermal performance during and after a specific disruptive event (Homaei et al., 2021). For this reason, building performance is evaluated over a short time frame (some days), differently from the robustness assessment. The performance indicator can be the indoor air or operative temperature, which is strongly related to occupants' comfort. Figure 3 shows a diagram reporting the performance indicator and the time frame adopted for thermal resilience assessment by Homaei et al. (2021). In this case, the authors define a resilient building as a building "*that is able* *to prepare in the initial state, absorb and adapt during the disruptive event and recover after the disruptive event"* (Homaei et al., 2021).

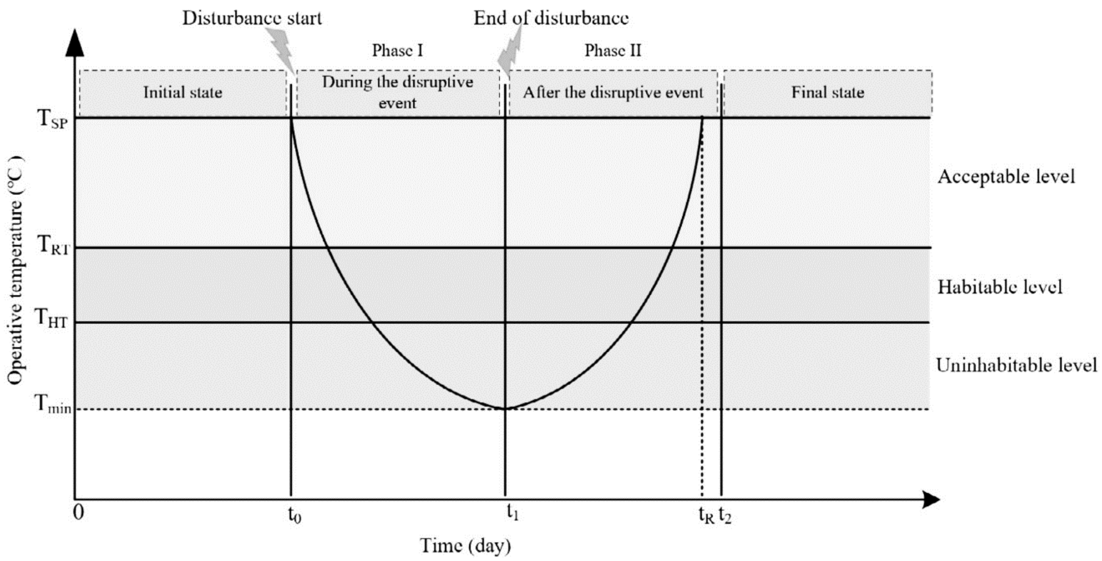


Figure 3. Conceptual illustration of curve for resilience assessment (Homaei et al., 2021)

Based on the literature review, common parameters affecting thermal resilience and similar performance indicators are identified and listed in Table 6, classified according to building envelope, building systems and renewable energy sources. Moreover, Table 7 reports the main variables controlled in the analyzed works to evaluate thermal resilience.

Table 6. Parameters affecting thermal resilience

Parameters affecting thermal resilience	
Building envelope	- Insulation thickness - Transmittance value - g-value of glazing - Wall solar absorptance - Roof solar absorptance - Wall thermal emissivity - Roof thermal emissivity
Building systems	<u>Heating and cooling system:</u> - Fan efficiency - Pump efficiency - Capacity of heating system - Capacity of cooling system - Generator efficiency <u>Ventilation system:</u> - Heat exchanger efficiency - Specific Fan Power
Renewable energy sources	- PV area - Battery size - Thermal storage capacity

Table 7. Thermal resilience performance indicators

Thermal resilience performance indicators	
Comfort performance	Indoor operative temperature [°C] Indoor air temperature [°C] Indoor relative humidity [%]

Since most buildings are highly dependent on external resources and infrastructure for providing energy services to occupants (Hewitt et al., 2019), resilience of buildings energy systems providing energy supply strongly contributes to the overall building resilience. In literature, studies focusing on energy systems resilience are frequent and involves different fields such as weather, technical failures, cyberattacks, geopolitics or energy sector (e.g., electricity, oil, and gas) (Jasiunas et al., 2021). Indeed, since modern societies are highly dependent on continued access to energy services, energy resilience is important and often meets the energy security concept. Energy security is defined by International Energy Agency (IEA) as "*uninterrupted availability of energy sources at an affordable price"* (IEA, 2022). In this sense, therefore, systems resiliency is "*a system ability to continue to serve its purpose, even during a shock or crisis"* (Hewitt et al., 2019), where energy supply is often the purpose. Systems resilience is quantified in different studies through various methods. For instance, Moslehi et al. (2018) have modelled "*systems response to potential internal and external failures during different operational temporal periods (such as different diurnal and seasonal periods of the year)"* and systems resilience is quantified upon loss in the services which the system is designed to provide. Wang et al. (2022), moreover, have deepened the solar energy contribution to energy resilience intended as energy security.

In conclusion, building resilience assessment, in terms of both thermal and energy resilience, is gaining importance in the building sector, considering the increasing frequency and intensity of various extreme disruptive events. Resilience features are essential to stand a complete failure of buildings functionality during extreme events, which means a reduced access to end-uses services to occupants and resulting potential risks for them (Hewitt et al., 2019). Resilient buildings, therefore, do not only have to withstand the unexpected events, but they also must be able to recover to acceptable performance level and continue their services even after the disruptive event occurrences (Moazami et al., 2019a).

2.4 Relation between robustness and resilience concepts

In the light of the above, resilience and robustness are different concepts and express two different properties, which main characteristics are summarized in Table 8.

Table 8. Robustness and resilience comparation

	Robustness	**Resilience**
Nature of considered uncertainties	Uncertainties during operation	Major disruptions or shocks
Required attributes for the protection against these uncertainties	Insensitivity of the building performance to the presence of uncertainties	Withstand, absorb and recover
For the built environment	The main focus is on aleatory uncertainties such as occupant's behavior and actions and climate	The main focus is on unforeseeable extreme events

However, some authors have shown the possible relation between resilience and robustness, as shown in Figure 4, realized by Moazami et al. (2019a), which represents the capacity of buildings to provide acceptable levels of performance and functional requirements. Figure 4 demonstrates that robust buildings present higher performances with lower sensitivity to uncertainties during to operational phase, when compared to non-robust and non-resilient buildings. Robust buildings, therefore, perform as expected during design or retrofit phase in case of typical and predictable uncertain conditions (e.g., occupants' behavior or foreseeable climatic situations) (Moazami et al., 2019a). Nevertheless, performance and functionality of robust buildings cannot be considered protected in case of unforeseeable extreme events, which may lead to the interruption of the building services. In such cases, resilience features are required. Indeed, a resilient building allows to withstand adversities and recovery from them, returning to the expected performance level and maintaining always available the building functionality (Moazami et al., 2019a).

From this description, we can conclude that the resilience definition includes the robustness one; if a building is resilient, it is expected to be also robust, while the opposite is not guaranteed. A robust building, indeed, is a building that, while in operation, can provide its performance requirements with a minimum variation in a continuously changing environment, while a resilient building can also withstand a major disruption (fulfill its functional requirements) and recover its performance to avoid permanent consequences (Moazami et al., 2019a).

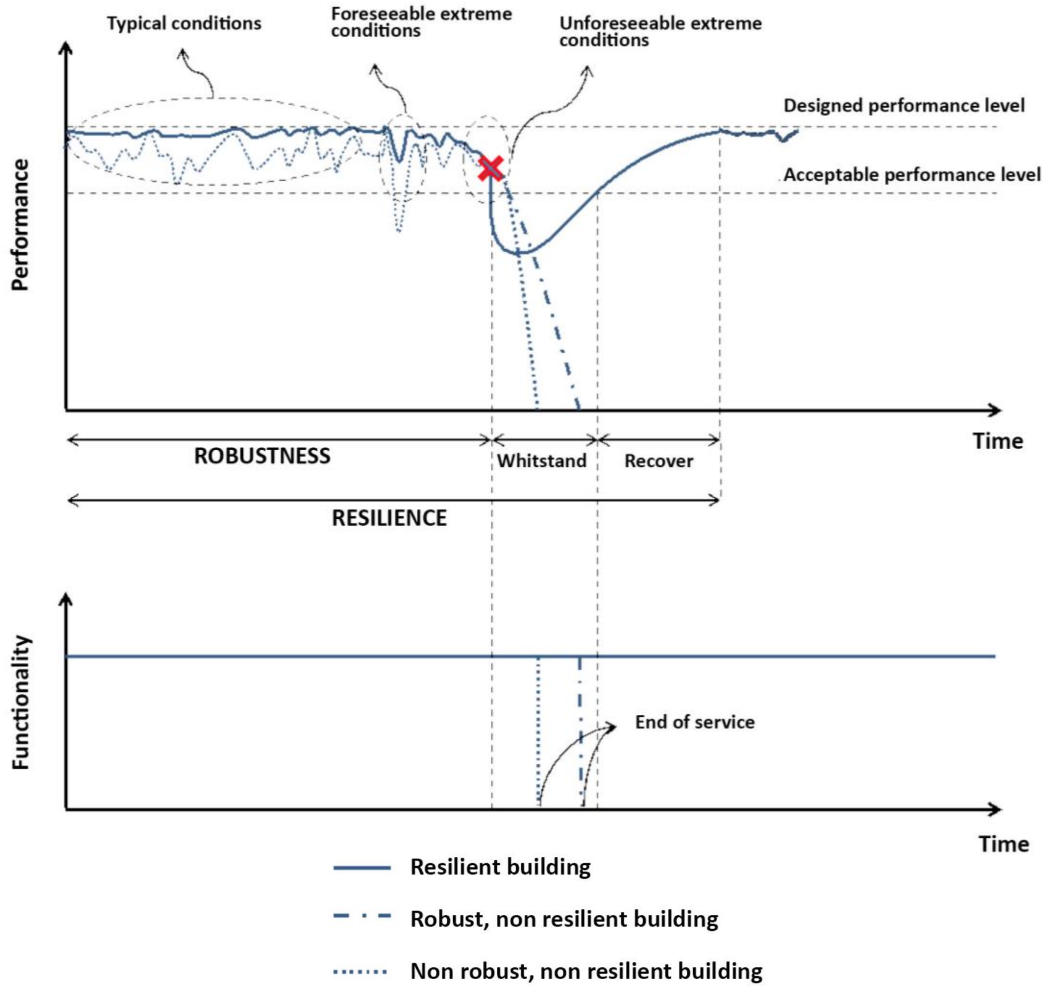


Figure 4. Framework for buildings robustness and resilience properties (Moazami et al., 2019a)

2.5 Strategies to enhance buildings robustness and resilience

The design of new constructions and the retrofit of existing buildings cannot be performed with the sole objective of achieving high energy performances, but it asks for the introduction of features capable of increasing their robustness and resilience, to deal with various uncertainties that can impact on their expected operations and performances. The sole purpose of sustainability, which, in the built environment, is translated into "green buildings" and their features (e.g., efficiency and decarbonization), is no longer sufficient. Sustainability has to encounter robustness and resilience goals; therefore, buildings "green" features should be synergic with "resilient" and "robust" features (Hewitt et al., 2019).

According to different studies the main factors that contribute to a robust and resilient building are:

1. Passive and active architectural features (e.g., building envelope and systems);
2. Building energy self-sufficiency (e.g., integration of renewable energy sources);
3. Occupants' actions.

All these factors are also considered while dealing with green buildings. Hewitt et al. (2019), indeed, argue that green buildings may offer more advantages in terms of resilience, and thus robustness, than ordinary buildings. Some of those advantages include more efficient systems, which can be shut down during emergencies, and on-site energy generation, which makes buildings more self-sufficient, reducing their dependence on external resource supply networks. In that sense, efforts to promote sustainability in green buildings can support also robustness and resilience (Hewitt et al., 2019).

In order to better define strategies and features capable of improving buildings robustness and resilience, two different phases involving buildings should be considered: design or retrofit phase and operational and management phase. Indeed, despite choices made in the first phase strongly contribute to the enhancement of robustness and resilience for buildings, also management actions undertaken during operational phase can contribute.

During design or retrofit phase robustness and resilience assessment through parameters and indicators previously described, come into play. From the results obtained from specific studies in literature, some common strategies and measures, referred to building envelope, building systems and renewable energy sources, are found to be effective to improve buildings robustness and resilience.

In detail, designing a well performing envelope or retrofitting the existing envelope by intervening on opaque and transparent envelope can, on the one hand, assure building performance robustness, in terms of energy consumptions and emissions, to climate change (e.g., increasing external temperatures)(Ascione et al., 2017) or other factors (e.g. occupants behavior) (Kotireddy et al., 2018). On the other hand, interventions on envelope can improve building thermal resilience, by ensuring acceptable thermal comfort even in the absence of building systems services, due to power outages potentially caused by extreme natural events (Homaei et al., 2021). As regards building systems, installing or replacing existing building systems with efficient and electricity-based systems, especially heat pumps, increase building performance robustness in terms of GHG emissions (Walker at. al, 2022; Galimshina et al., 2020). Furthermore, efficient and electricity-based systems can support building resilience in case of possible atypical operation conditions during a shock event (Hewitt et al., 2019), especially when combined with systems for the exploitation of renewable energy sources or batteries. Indeed, the introduction on photovoltaic systems and electricity storage batteries can provide robust building solutions in terms of GHG emissions, especially in countries where the carbon intensity of the electricity grid mix is significantly higher (Walker et al., 2022), and improve building thermal resilience in case of power failure, implementing building energy self-sufficiency which guarantee systems functionality (Homaei et al., 2021; Sun et al., 2020).

Focusing on the operational phase, the main contribution is given by occupants' actions and choices taken for building management. In this case, it is not always easy to quantify the impact of occupants' actions, but some qualitative indications and suggestions can be given to support buildings robustness and resilience. In this regard, a relatively recent concept may be interesting: household energy resilience. The term "household" refers to a group of people living in the same house, characterized by their own everyday practices and good life idea (Hasselqvist et al. 2022). Despite buildings systems and equipment, household can play an important role when it comes to face expected and unexpected future energy disturbances. In this regard, Hasselqvist et al. (2022), have suggested a definition of household energy resilience which states: "*As an interwoven part of everyday life, household energy resilience is to ensure a good life through adjusting what activities that are performed, when they are performed and how they are performed in the face of expected and unexpected power outages and shortages as well as to prepare for future adjustments of activities and to more fundamentally change to reduce the need for adjustments".* Figure 5 graphically shows such concept.

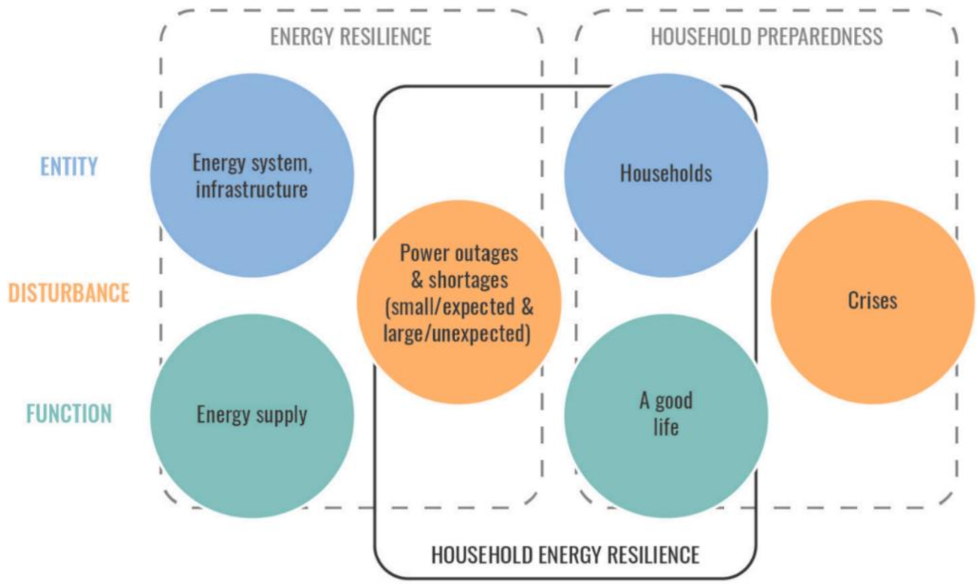


Figure 5. Household energy resilience framework (Hasselqvist et al., 2022)

Table 9 and Table 10 report some qualitative strategies, addressed to households to enhance buildings robustness and resilience, which are collected from different studies.

Table 9. Robust building operation and management: robustness enhancement strategies

Robustness enhancement strategies – Operation and management phase	
Household lifestyles and preferences	Optimize daily setpoints temperature for cooling and heating, windows opening and solar shading in order to allow a higher robustness in terms of energy performance and thermal comfort.
Reference studies: Barthelemes et al., 2016; Kotireddy et al., 2018; Moazami et al., 2019b; Rouleau et al., 2019; Sun et al., 2020; Walker et al., 2022	

Table 10. Resilient building operation and management: resilience enhancement strategies

Resilience enhancement strategies – Operation and management phase	
Household energy resilience	Energy efficiency: use of more efficient appliances and systems, with sufficient capacity.
	Flexibility: in terms of adapting electricity use to the current supply (changing time of activities and changing place for activities).
	Energy sufficiency: quitting energy-intensive activities, replacing activities, replacing products for smaller/ lower capacity ones, appliances with variable power options, use of backup energy sources, using electricity that is stored locally or generated from other energy sources (e.g., generators, solar and wind power, or human power).
Reference studies: Hasselqvist et al., 2022; Wang et al., 2022; Chintavali et al., 2022	

In conclusion, in order to make buildings prepared to face future challenges, including sustainability goals and capacity to deal with diverse uncertainties, all phases of buildings life cycle are involved. The design and retrofit phase of a building should focus both on the improvement of its energy performance and on the guaranteeing of robustness and resilience, in order to meet both mitigation and adaption purposes. Indeed, on the one hand, buildings must reduce consumptions and emissions to mitigate their impacts on the environment and society. On the other hand, buildings must present features capable of make them adaptive against inevitable future predictable and unpredictable uncertainties and events. Moreover, besides the importance of the design/retrofit phase to obtain efficient and prepared buildings, household actions during the operational and management phase also contribute to the achievement of the main challenges of future buildings: the spreading of green/sustainable, robust and resilient buildings.

3. Methodology

The thesis proposes a methodological approach aiming to identify and assess diverse retrofit strategies for existing buildings, in the light of the three main goals of the future buildings (i.e., sustainability, robustness and resilience), to increase both their energy efficiency and their robustness and resilience to potential future stresses.

For the analysis to be generalized and extended to the stock level, a reference building (or archetype) approach was adopted; this method is valid to understand the potentialities of specific renovation interventions, applied to selected representative buildings, identified as prevalent building typologies, in terms of energy savings, emissions reduction and enhancement of robustness and resilience properties, in case these interventions would be "*applied to all buildings of similar program type, age or category*" (Corgnati et al., 2013).

An archetype is defined as "*a statistical composite of features found within a category of buildings in the stock*" (ECBCS, 2004). By presenting specific buildings characteristics (e.g., typology, location, period of construction, geometrical feature, etc.), archetypes can be considered representative of a portion of a wider building stock. Consequently, having assessed the energy performance of a set of selected archetypes, it would be possible to extend these considerations and results to the whole building stock the archetypes are representative of. In addition to evaluating the current state of a given building stock, archetype approach allows to perform energy-related scenario analysis (Streicher et al., 2019). Therefore, the retrofit scenarios assessed for the selected archetypes by introducing strategies to increase buildings efficiency, resilience, and robustness, would help estimating the impact of the implementation of these specific measures at a larger building stock scale.

The approach described above is adopted to identify different retrofit solutions responding to the main goals of the thesis: sustainability, robustness, and resilience. The main methodological steps pursued in the work are the following:

1. Definition and modelling of building archetypes through the investigation of the building stock under investigation.
2. Current state assessment of building archetypes:
    a. Quantitative assessment of buildings energy and environmental performance through the calculation of relevant annual indicators (e.g., energy needs, consumptions, emissions).
3. Definition and modelling of possible energy retrofit strategies related to building envelope, energy systems, and renewable sources integration.
4. Retrofit scenarios assessment of building archetypes:

a. Quantitative assessment of buildings energy and environmental performance improvement through the calculation of relevant annual indicators (e.g., energy needs, consumptions, emissions).
b. Qualitative assessment of buildings robustness and resilience levels enhancement.

The methodology described so far is tailored on the case study deepened in this thesis work, the building stock of Pantelleria Island, which is characterized by the presence of traditional *dammusi* buildings. The assumptions done for the study and the main results achieved are described in the following chapters.

4. Pantelleria Island as case study: background and motivations

Islands all over Europe are undertaking clean energy transition processes since they still largely depend on fossil fuels imports for their energy supply, despite local availability of renewable energy sources. The European Commission aims to accelerate their energy transition through the Clean Energy for EU Islands Initiative, which provides support and resources (EC, 2017)

In this frame, Pantelleria Island is one of the three Italian islands selected by the Clean Energy for EU Islands Secretariat as pioneer island for a high-quality energy transition. Pantelleria Island is not interconnected to the national power grid and mostly depends for its energy supply from diesel systems, despite there are some distributed systems for the exploitation of renewable resources (CNR-IIA, 2021). Fossil fuels, used for both final uses and electricity production, are transported by tankers by sea resulting in a surcharge for end-users, implying, thus, bad consequences at both environmental and economic levels.

According to the "*Agenda per la Transizione Energetica"* (2020) of the Pantelleria Island, electricity is the main energy carrier, accounting for 43% of final energy consumptions, as is shown in Figure 6.

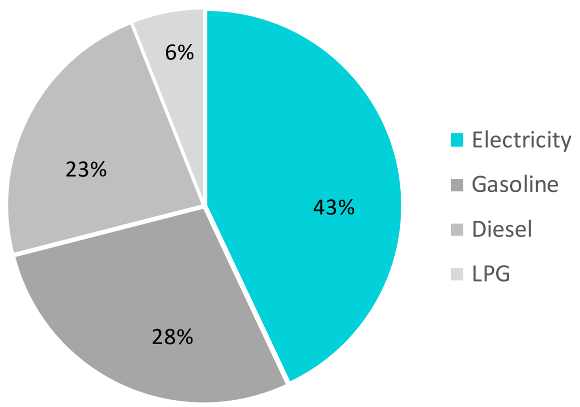


Figure 6. Final energy consumptions on Pantelleria Island (Elaboration from Agenda per la Transizione Energetica)

The largest share of electricity consumption, which is equal to 38%, is due to the residential sector, considering both permanent and summer holiday houses. Indeed, electricity meets most energy needs for space heating, space cooling and domestic hot water production. According to "*Piano D'Azione per l'Energia Sostenibile del Comune di Pantelleria"* (2015), indeed, space heating is almost exclusively provided by electric heaters. Furthermore, domestic hot water production is mainly provided by hot water storage heaters, which are responsible for 30% and 37% of final electricity consumptions, for permanent houses and summer holiday houses respectively, as shown in Figure 7 and in Figure 8.

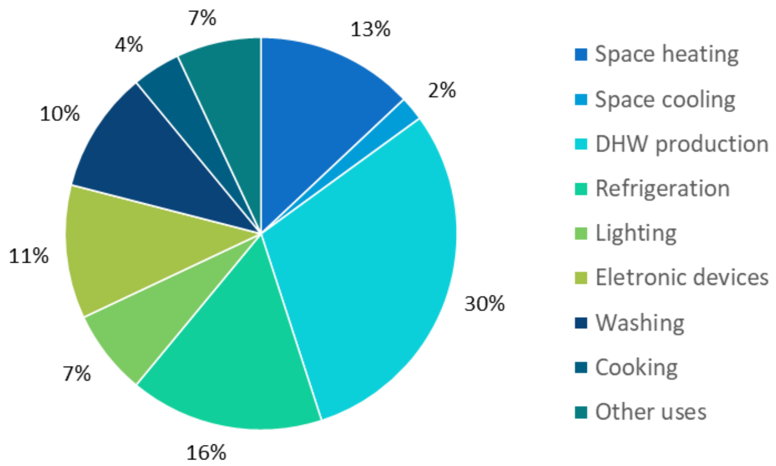


Figure 7. Final electricity consumptions for permanent houses (Elaboration from "Piano D'Azione per l'Energia Sostenibile del Comune di Pantelleria")

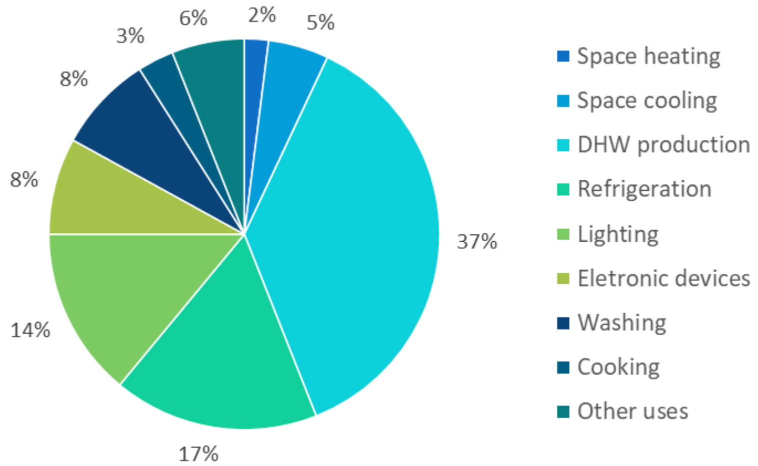


Figure 8. Final electricity consumptions for summer holiday houses (Elaboration from "Piano D'Azione per l'Energia Sostenibile del Comune di Pantelleria")

Moving to renewable sources, according to "*Agenda per la Transizione Energetica"* (2020), the residential sector self-sufficiency is low; specifically, the document provides an indicator, namely the self-sufficiency level, which is defined as the ratio between the amount of energy self-produced, through on-site renewable energy sources, and the total energy consumed by the sector. This indicator for the residential sector of Pantelleria is only 1%.

Finally, moving to the environmental sphere, according to "*Piano D'Azione per l'Energia Sostenibile del Comune di Pantelleria"* (2015), the residential sector accounts for 25.8 % of total CO_{2eq} emissions, as shown in Figure 9.

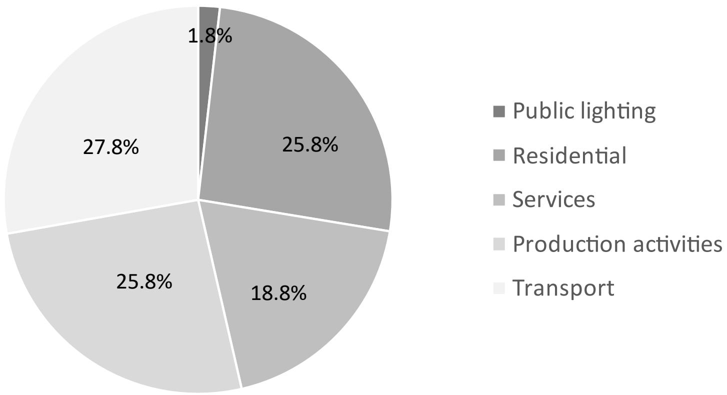


Figure 9. CO_{2eq} emissions according to sectors
(Elaboration from "Piano D'Azione per l'Energia Sostenibile del Comune di Pantelleria")

4.1 Decarbonization and energy transition: Pantelleria Island future targets

Pantelleria Island, in the "*Agenda per la Transizione Energetica*" (2020), has identified the following six pillars for energy transition in order to achieve full decarbonization by 2050:

1. Energy efficiency and consumptions reduction;
2. Electricity production from renewable energy sources;
3. Buildings energy self-sufficiency and distributed energy production;
4. Sustainable mobility;
5. Energy storage;
6. Creation of energy communities.

In parallel with consumptions reduction and final uses electrification, the installation of distributed systems for the exploitation of on-site renewable energy sources aims at reaching 80% of electricity self-sufficiency and 85% of thermal energy needs coverage for the residential sector. In the "*Agenda per la Transizione Energetica*" (2020), five-year objectives to support island energy transition are set, including those referred to energy self-sufficiency for residential sector and CO_{2eq} emissions reduction, which are shown in Figure 10 and 11.

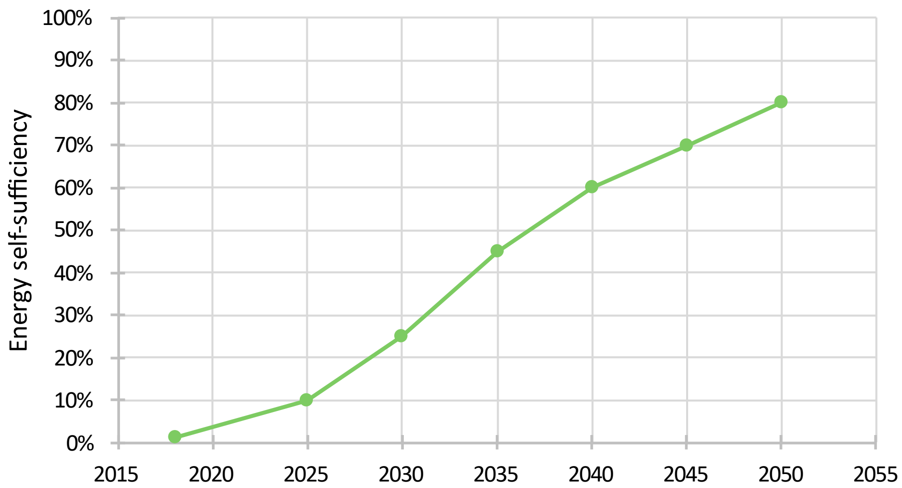


Figure 10. Objectives for residential sector energy self-sufficiency (Elaboration from "Agenda per la Transizione Energetica")

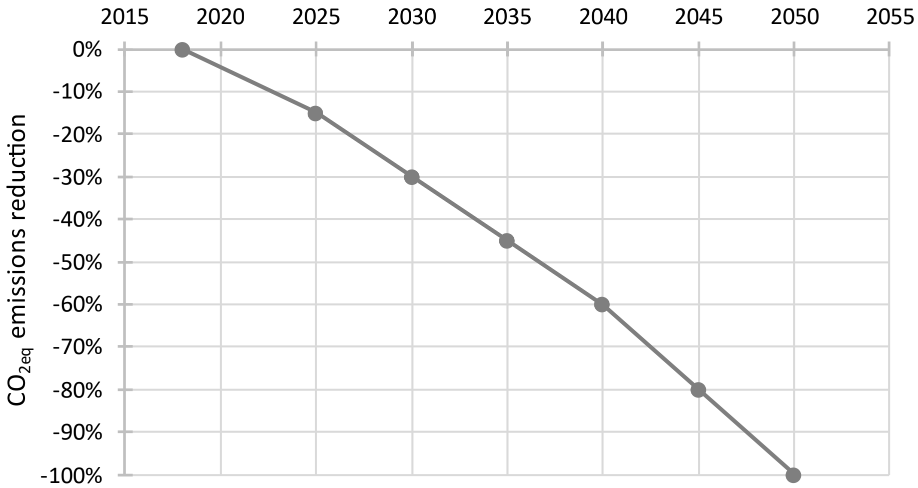


Figure 11. Objectives for CO_{2eq} emissions reduction (Elaboration from "Agenda per la Transizione Energetica")

Therefore, the decarbonization process involving particularly the residential sector is driven by energy efficiency, electrification, and use of on-site renewable energy source. Despite the implementation of these actions is fundamental with a view to mitigation, the same should be able to increase buildings robustness and resilience level to face inevitable future predictable and unpredictable uncertainties and events. In fact, Sicily, and thus Pantelleria, is already and will be one of the most severely European regions affected by the increase of external temperatures in summer (Van Maanen et al., 2022), as a consequence of climate change and global warming issues, affecting the building sector and tourism, which is one of the main economic resources of the island during summer months. Furthermore, local power grid, which mostly depends for its energy supply from diesel systems and is currently already unstable, could end up without source of energy and could experience power congestion and outages due to peaks of energy demand deriving from buildings electrification (especially during summer, due to higher occupancy level). Then, robustness and resilience goals should be introduced and persecuted to reduce uncertain events impacts on existing building stock future performance, ensuring in any case high energy performance and inhabitants and tourists' comfort. Consequently, adaptation and mitigation strategies need to be pursued simultaneously by the existing building stock of Pantelleria Island, by addressing the main challenges of the future, which are decarbonization, robustness and resilience.

4.2 Pantelleria Island regulatory framework

This paragraph summarizes the Pantelleria Island applicable regulations at national, regional and local level, including both the legislation to support smaller islands energy transitions and the legal limitations to renewable sources exploitation, such as environmental and landscape constraints.

Current legislation and regulations, however, focus only decarbonization and related actions to undertake with a view to mitigation strategy, without mentioning robustness and resilience importance against uncertain events. This highlights the fact that, despite adaption strategy is outlined, no operating indication is yet provided for by policy makers. This should be a way to deepen in the future.

NATIONAL LEGISLATION

National legislation concerning climate and energy production and supply includes:

- *"Piano Nazionale Integrato per l'Energia e il Clima"* (2020): the plan sets national 2030 targets in terms of energy efficiency, renewable energy sources and CO_{2eq} emissions.
- *"Decreto Ministeriale 14/02/2017. Disposizioni per la progressiva copertura del fabbisogno delle isole minori non interconnesse attraverso energia da fonti rinnovabili": it promotes the realization of systems for the exploitation of renewable energy sources for private customers.*
- *"Decreto del Presidente della Repubblica 4/6/2013 n. 63 […], Disposizioni urgenti […] sulla prestazione energetica nell'edilizia per la definizione delle procedure d'infrazione avviate dalla Commissione europea, nonché' altre disposizioni in materia di coesione sociale": it concerns tax deductions between 50% and 85% to improve buildings energy efficiency.*

However, on the matter of naturalistic and landscape aspects, the "*Decreto del Presidente della Repubblica 7/10/2016 n. 235, Istituzione del Parco nazionale «Isola di Pantelleria» e dell'Ente Parco nazionale «Isola di Pantelleria»"* established National Pantelleria park. Renewable energy sources exploitation is promoted within the territory of the park even if the construction of renewable energy plans is subject to park authority authorization. Park territory is divided into three zones, each of which is characterized by different constraints. Figure 12 illustrates Pantelleria Island Park zoning.

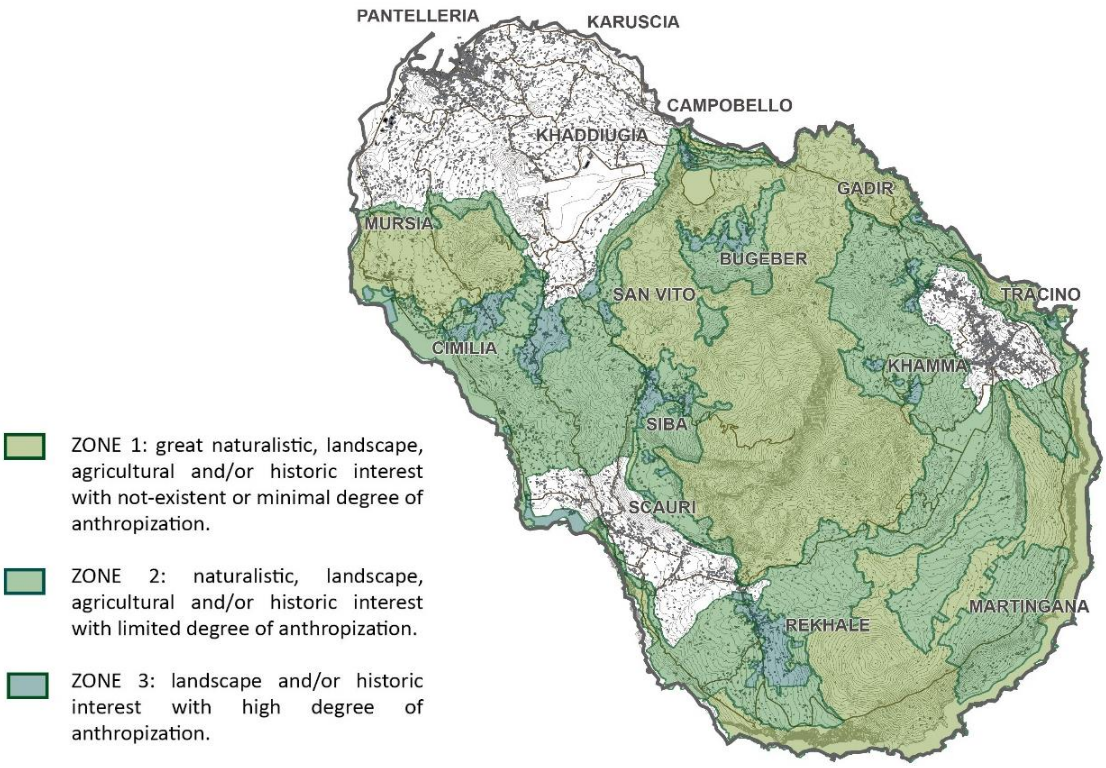


Figure 12. "Parco Nazionale dell 'isola di Pantelleria" zoning
(Elaboration of "Proposta di Perimetrazione e Zonazione del Parco Nazionale di Pantelleria" provided in DPR 235/2016 on the basis of C.T.R 1:10000 shapefiles)

REGIONAL LEGISLATION

Regional legislation concerning climate and energy production and supply includes:

- *"Piano Energetico Nazionale della Regione Siciliana" (2019, update to 2021):* the plan sets regional 2030 targets with a view to energy transition and Pantelleria Island is identified as pioneer island in this process.
- *"Decreto Presidenziale 10/10/2017, Definizione dei criteri ed individuazione delle aree non idonee alla realizzazione di impianti di produzione di energia elettrica da fonte eolica […]": it identifies not suitable areas for the realization of eolic plants; among these there is Pantelleria Island territory.*

According to “*Decreto Assessoriale 26/07/1976, Dichiarazione di notevole interesse pubblico dell’isola di Pantelleria”*, the whole Pantelleria Island territory, with the exception of the town, is declared as a zone of “significant public interest”. Therefore, it is subject to a landscape constraint as required by “*Decreto Assessoriale 12/12/1997 n. 8102, Piano territoriale paesistico dell’isola di Pantelleria”*. The Decree prohibits the solar and eolic plants installation on buildings roofs. Moreover, it is required Superintendence authorization to install them on ground.

LOCAL LEGISLATION

Technical standards for implementation related to general urban development plan, the “*Piano Regolatore Generale del Comune di Pantelleria, Norme Tecniche di Attuazione”* (2014), regulate the interventions on existing *dammusi* buildings, providing constraints to preserve the architectural heritage of the island, which is the *dammusi* buildings stock.

Specific constraints concerning different aspects of the *dammusi* buildings are deepened in the next chapter. Among these is the prohibition of solar and eolic plants installation on *dammusi* roof.

4.3 The NESOI EU Project

The thesis has been developed in collaboration with the TEBE-IEEM Research Group of the Energy Department of Politecnico di Torino, in the framework of the European project supported by EU Island Facility NESOI (New Energy Solutions Optimised for Islands), named the RENEWDAMMUSI project. The NESOI EU Project is part of Horizon Europe program 2020, Clean Energy for EU islands project, which is addressed to 2400 inhabited EU Island, including Pantelleria.

In this frame, the RENEWDAMMUSI project focuses on the energy retrofit of the local building stock, mainly constituted by the traditional residential building typology, the *dammusi,* in order to increase the building stock energy efficiency and to enable a larger deployment of on-site renewable energy sources. These measures are essential to cut buildings energy demand and energy consumptions and tackle greenhouse gas emissions produced by the local building stock. The final purpose of the project is the creation of a set of technical guidelines addressed to local designers, to support future interventions on *dammusi* buildings, enabling the implementation of ad-hoc energy efficiency measures on Pantelleria Island buildings.

The RENEWDAMMUSI project concerns the decarbonization process of the existing building stock, with a view only to mitigation strategy, which aims at achieving the energy and emissions reduction targets set out for 2030 by European legislation. Starting from this, the thesis goes one step further towards adaptation goals, also including a qualitative assessment of the capacity of the energy efficiency measures, proposed for *dammusi* buildings energy retrofit, to also improve their robustness and resilience to uncertainties. This consideration is particularly interesting given the specificity and challenges of the geographical context under investigation, which will be deepened in the next paragraph.

5. Application

5.1 Definition and modelling of *dammusi* archetypes

Starting from a preliminary analysis of the existing building stock of Pantelleria Island, this step consists in the study of the main features of existing *dammusi* buildings, aiming to define and model a set of archetypes.

5.1.1 Analysis of the existing stock and study of *dammusi* features

At first, in order to investigate and deepen the knowledge on the existing building stock of Pantelleria Island, characterized by *dammusi*, the traditional residential buildings, a critical analysis of reference documentation and existing literature is carried out, jointly with constant dialogue with the local authority "*Ente Parco Nazionale Isola di Pantelleria*" (PNIP).

The results of the investigation are collected in two abacuses, which report the main characteristics of traditional local *dammusi* buildings stock. The first abacus, "Abacus of *dammusi* building typologies", identifies the following six local prevalent *dammusi* building typologies, considering their geometry and rooms layout:

- *Dammuso monocellula*
- *Dammuso doppia cellula*
- *Dammuso tripartito*
- *Dammuso per aggregazione complessa*
- *Dammuso per aggregazione complessa con elementi accessori e pertinenze*
- *Dammuso palazzetto*

The second abacus, "Abacus of *dammusi* building components", summarizes the main features and regulatory constraints of *dammusi* components (opaque/transparent envelope and systems).

In general, *dammusi* are made by stone bearing walls. *Dammusi* façade can have exposed stone or can be plastered, while internal surfaces of the walls are almost always plastered. Each room is covered by its own vault, which can be of different type. *Dammusi* roofs are externally coated with a traditional waterproofing finish layer made up of tuff and lime which has a light color. The internal surface of vaults, instead, is nearly always plastered. The ground floor consists of a concrete conglomerate layer realized on a pebbles and crushed stone layer. The walls have a few openings, including the entrance, which is characterized by a wooden door, and small windows. Windows are set back from the edge of the façade and their frame is made of wood. An outdoor shading system, the *cannizzato*, is present to cover the external space next to the building. The *cannizzato* is made of natural materials (wood and reeds) and has spread in recent years, becoming a traditional element.

Regarding buildings energy systems, no systems for space heating and space cooling are present in most *dammusi* buildings. According to "*Piano D'Azione per l'Energia Sostenibile del Comune di Pantelleria"* (2015), space heating is mainly provided by electric heaters. Domestic hot water production, instead, is almost exclusively provided by hot water storage heaters. Therefore, electricity is the main employed energy carrier. Electricity is mainly taken from local power grid and renewable energy sources are not currently exploited. Figure 13 shows representative photographs of the traditional *dammusi* buildings.

Figure 13. Representative photographs of dammusi buildings

The *dammusi* are subject to existing limitations and constraints for the protection of the historical and architectural heritage of the island, which can restrict potential energy interventions on them. The main regulatory constraints specifically referred to *dammusi,* which are classified according to building envelope, building systems and renewable energy sources, are summarized in Table 11. These constraints provide the basis for setting out alternative strategies for energy retrofit of residential *dammusi* buildings.

Table 11. Main regulatory constraints referred to dammusi buildings

Regulatory constraints	
Building envelope	Walls: - It is not allowed to realize façade cladding alien to traditional types (brick and marble) - Plastering stone façade is not permitted - Façade plaster must be made up of lime and sand Windows and doors: - Windows and doors frame must be made of wood - Windows and doors must be set back from the edge of the façade - Roller shutters are not allowed Roof: - It is not allowed to install false ceiling on vaults - External roof surface must be waterproofed with a tuff and lime layer
Building systems	Systems installation: - No specific constraints are expressed on systems installation are expressed
Renewable energy sources	Systems installation: - It is not allowed to install photovoltaic panels or solar thermal panels on *dammusi* roofs
Reference documents: *- Piano Territoriale Paesistico dell'isola di Pantelleria, Norme di Attuazione (2000)* - Piano Regolatore Generale del Comune di Pantelleria, Norme Tecniche di Attuazione (2014)	

The two complete abacuses, reporting detailed information about existing *dammusi* buildings characteristics and related constraints, are compiled in Italian language, to preserve the local technical terms specific for *dammusi* buildings, and are reported in Appendix section.

5.1.2 Description of *dammusi* archetypes and related energy models

According to information collected and organized into the two abacuses, the following three different *dammusi* building archetypes are identified:

- Archetype 1: *Dammuso tripartito*
- Archetype 2: *Dammuso per aggregazione complessa*
- Archetype 3: *Dammuso per aggregazione complessa con elementi accessori e pertinenze*

The other prevalent building typologies previously identified are not included because of their non-residential use (*Dammuso monocellula*) or their limited frequency on the island (*Dammuso palazzetto*).

Consequently, the energy model for each *dammuso* archetype is built and simulated using the software Edilclima, version 11.22.10, which performs quasi-steady state energy simulations. The main steps pursued to develop archetypes energy models are the following:

- Setting of local climatic data;
- Description of input related to occupancy;
- Geometry and thermal zone definition for each archetype;
- Identification of thermo-physical features of the building envelope for each archetype;
- Building systems implementation for each archetype.

Subsequent sections report in detail the main step to develop the three archetypes models, describing their main features.

CLIMATIC BOUNDARY CONDITIONS

The typical weather conditions of Pantelleria Island refer to the Italian Standard for conventional climatic data UNI 10349-1:2016. Table 12 lists the main climatic data and Figure 14 shows the profile of the average external temperature.

Table 12. Climatic data of Pantelleria Island

<table>
<tr><th colspan="12">MAIN CLIMATIC DATA</th></tr>
<tr><td colspan="8">Municipality</td><td colspan="4">Pantelleria</td></tr>
<tr><td colspan="8">Province</td><td colspan="4">Trapani</td></tr>
<tr><td colspan="8">Climatic zone</td><td colspan="4">B</td></tr>
<tr><td colspan="8">Heating Degree Days (DPR 412/93)</td><td colspan="4">717</td></tr>
<tr><td colspan="8">Cooling Degree Days (DOE EnergyPlus weather data)</td><td colspan="4">903</td></tr>
<tr><th colspan="12">Heating season</th></tr>
<tr><td colspan="8">External design temperature</td><td colspan="4">5°C</td></tr>
<tr><td colspan="8">Heating period</td><td colspan="4">1st December – 31st March</td></tr>
<tr><th colspan="12">Cooling season</th></tr>
<tr><td colspan="8">External design temperature (DOE EnergyPlus weather data)</td><td colspan="4">34.4 °C</td></tr>
<tr><th colspan="12">Monthly average external temperature
[°C]</th></tr>
<tr><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th></tr>
<tr><td>11.3</td><td>11.1</td><td>13.0</td><td>15.7</td><td>20.9</td><td>24.0</td><td>26.6</td><td>27.7</td><td>22.6</td><td>19.8</td><td>16.4</td><td>13.9</td></tr>
</table>

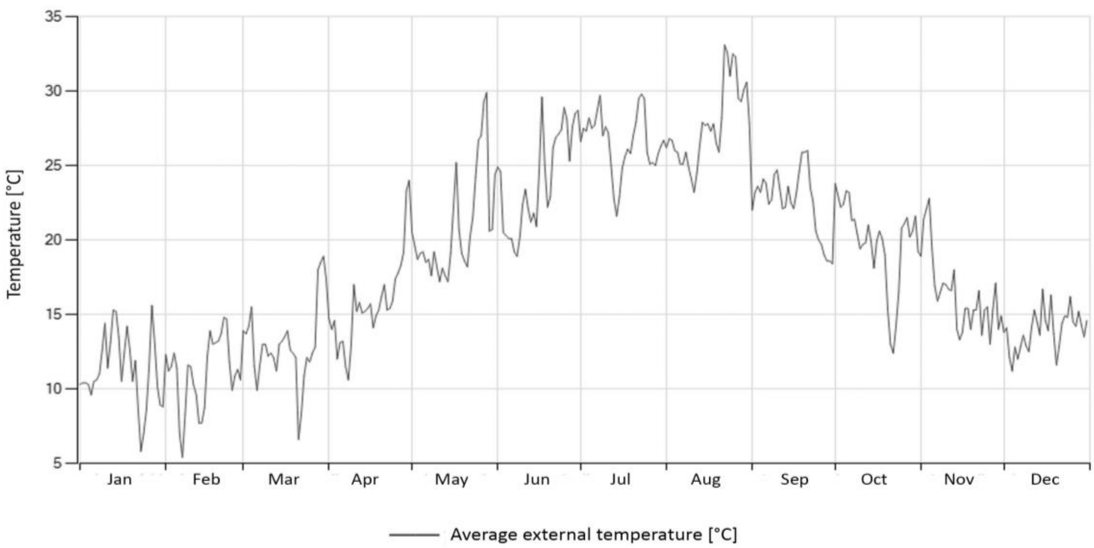


Figure 14. Average external temperature of Pantelleria Island

INPUT DATA RELATED TO OCCUPANCY

The building category selected according to DPR 412/93 is E.1(1) (residential buildings, continuous occupation). The calculations are performed by considering the standard occupancy defined by the UNI/TS 11300-1:2014 with the following assumptions:

1. Natural ventilation with outdoor flow rate constantly sets to 0.3 ACH, according to a residential use;
2. Simplified approach to calculate internal heat gains (people, equipment and lighting), depending on the net floor area of dwellings; internal heat gains are equal to 6.99 W/m^2, 5.91 W/m^2 and 12.56 W/m^2, respectively for Archetype 1, Archetype 2 and Archetype 3. Internal gains are calculated as shown in Eq. (1):

   $$\Phi_{int} = 7.987\ A_f - 0.0353 \times A_f^{\ 2} \quad (1)$$

   where A_f is the conditioned net floor area;
3. Heating and cooling set-point temperatures fixed equal to 20 °C and 26 °C, respectively.

ARCHETYPE 1: *DAMMUSO TRIPARTITO*

GEOMETRIC DATA

The case study is a 53 m^2 isolated *dammuso* located in Pantelleria. The building is characterized by one floor with, a conditioned net floor area of about 28 m^2 and a conditioned net volume of 79 m^3. The building is modeled through a single conditioned thermal zone.

The archetype building plan and the thermal zones map are presented in Figure 15, while Table 13 lists the main geometric data of the building.

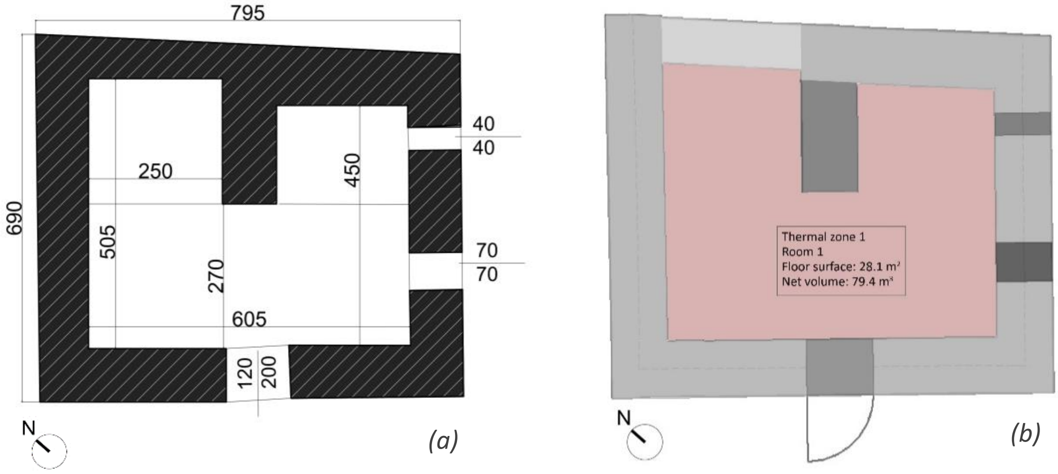


Figure 15. Dammuso plan (a) and dammuso model with thermal zone (b)

Table 13. Main geometric data

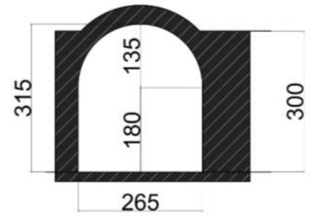
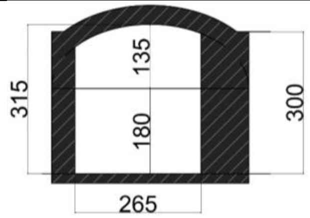
Net conditioned floor area [m^2]	**Gross conditioned floor area** [m^2]	**Net conditioned volume** [m^3]	**Gross conditioned volume** [m^3]	**Building components area** [m^2]	**Aspect ratio** [m^{-1}]
28.1	52.8	79.4	185.0	213.8	1.16

Each room is covered by its own vault. In order to adequately model the vaults of the rooms and, consequently, their volume, the following requirements are considered:

1. The average height of the vault springer is 1.8 m and the average height of the external walls is 3 m (Giardina, 2018);
2. The minimum radius of curvature of the vault, to be considered a traditional Pantelleria vault, must be equal to half of the smaller dimension of the room with a tolerance of 40 cm. Furthermore, the maximum height must not exceed 4 m (PRG, 2014).

All types of vaulted roofs are approximated to a barrel vault typology due to a limitation of the modeling software. Consequently, the real section of a room of the *dammuso* and the corresponding section modeled by the software are different. Nevertheless, the modeled one can well approximate a typical section. A comparison between the two sections is provided in Table 14 and Figure 16 shows a 3D view of the modeled building.

Table 14. Comparison between real and modeled section

<table>
<tr><th colspan="2">Real section</th><th colspan="2">Modeled section</th></tr>
<tr><td colspan="2">
</td><td colspan="2">
</td></tr>
<tr><td>Room volume [m³]</td><td>Roof area [m²]</td><td>Room volume [m³]</td><td>Roof area [m²]</td></tr>
<tr><td>46.0</td><td>17.1</td><td>49.0</td><td>18.8</td></tr>
</table>

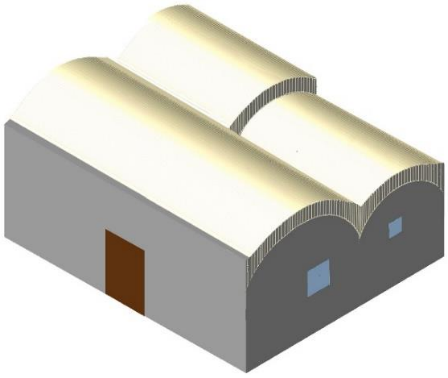


Figure 16. 3D view of the building

Table 15 reports the building components area according to the different orientation.

Table 15. Building components area divided according to orientation

Orientation	**Building components area** [m^2]				
	Walls	***Doors***	***Windows***	***Floor***	***Roof***
NE	27.2	-	-	-	33.8
SE	11.6	-	0.65	-	-
SW	26.9	2.6	-	-	33.8
NW	24.6	-	-	-	-
HOR	-	-	-	52.8	0.26

THERMO-PHYSICAL CHARACTERISTICS OF THE BUILDING ENVELOPE

The structure and the envelope of the typical *dammuso* are made by stone bearing walls. The vaulted roofs are made by stones. The ground floor is made by concrete conglomerate and is leaned on ground.

Wall components are identified by *M* code and number 1 to 3. Floor is identified by code *P1*. Roof components are identified by code *S1*. Window components are identified by *W* code and number 1-2 and door is identified by code *D1*. All the envelope components identification codes are provided in Figure 17.

The building envelope thermo-physical properties adopted in the model are mainly taken from the experimental measurements for a typical *dammuso* provided in Rodonò et al. (1980). The lime and sand plaster thermo-physical features are derived from UNI EN ISO 10456:2008.

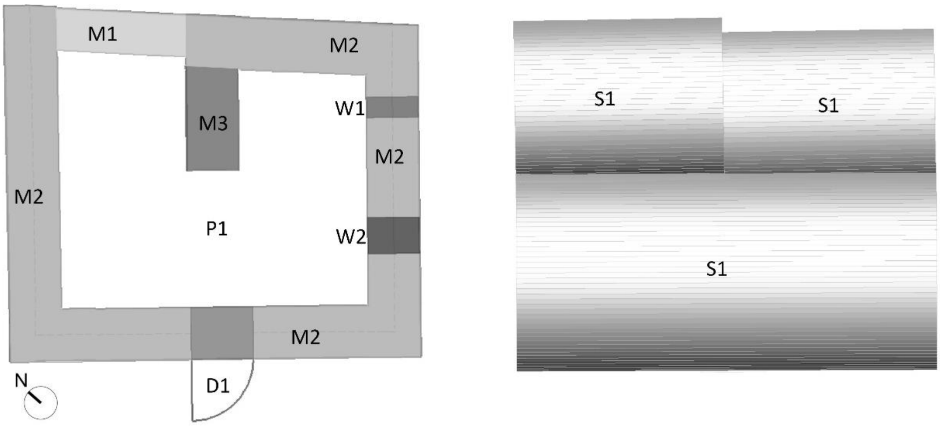


Figure 17. Building and roof plan - envelope components identification codes

Building opaque envelope: walls

The walls are characterized by different thicknesses and the absorption factor is assumed equal to 0.6. The wall stratigraphy and its materials average thermo-physical features are reported in Table 16. Table 17 summarizes the main wall components thermo-physical features. Two types of walls are identified in the model:

- T type wall separates conditioned room from external
- D type wall represents conditioned zone internal separation

Table 16. Wall stratigraphy and materials average thermo-physical features

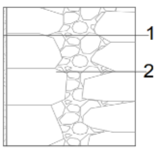
Stratigraphy	N	Layer description	Thickness	Conductivity	Density	Heat Capacity	Dry water vapour resistance
			[m]	[W/mK]	[kg/m^3]	[kJ/kgK]	[-]
	1	Lime and sand plaster	0.02	0.80	1600	1	10
	2	*“Casciata”* wall	1.00	0.81	2000	0.84	50

Table 17. Wall components thermo-physical features

Code	Thickness	Surface mass	Thermal Transmittance
	[m]	[kg/m^2]	[W/m^{2}K]
T type walls: from conditioned room to external			
M1	0.80	1560	0.85
M2	1.00	1960	0.70
D type walls: conditioned zone internal separation			
M3	1.00	1920	0.67

Building opaque envelope: doors

The modeled door components are constituted by a wood panel. The doors materials thermo-physical features are derived from UNI 10351:2021 and are listed in Table 18. Door components thermo-physical features are reported in Table 19.

Table 18. Door materials thermo-physical features

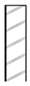
Component	Description	Thickness	Thermal Resistance	Density	Heat Capacity
		[m]	[m^2K/W]	[kg/m^3]	[kJ/kgK]
	Pine wood: fiber perpendicular flow	0.03	0.21	550	1.6

Table 19. Door components thermo-physical features

Code	Thickness	Surface mass	Thermal Transmittance
	[m]	[kg/m^2]	[W/m^2K]
T type door: from conditioned room to external			
D1	0.03	17	2.45

Building transparent envelope: windows

The modeled window components are constituted by a single layer of glass and by a wood frame. The glass and frame transmittance values are provided by Annex B of the technical Standard UNI/TS 11300-1:2014. Windows transmittance values for climatic zone B are derived from Ballarini et al. (2017) and Corrado et al. (2014). Window components thermo-physical features are reported in Table 20.

Table 20. Window components thermo-physical features

Code	Description	Solar transmittance factor	Glass Thermal Transmittance	Frame Thermal Transmittance	Window Thermal Transmittance
		[-]	[W/m^2K]	[W/m^2K]	[W/m^2K]
T type: from conditioned room to external					
W1	Single glass and wood frame window	0.85	5.7	1.6	4.9
W2	Single glass and wood frame window	0.85	5.7	1.6	4.9

Building opaque envelope: ground floor

The ground floor is assumed leaned on ground. The ground is characterized by a conductivity equal to 0.93 W/mK. The ground floor consists of a concrete conglomerate layer realized on a pebbles and crushed stone layer. The floor stratigraphy and its materials thermo-physical features are reported in Table 21. Table 22 summarizes the main thermo-physical features of the floor components. The floor type identified in the model is the following:

- G type floor separates conditioned room from ground

Table 21. Ground floor stratigraphy and materials thermo-physical features

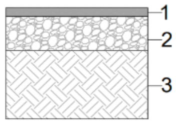
Stratigraphy	**N**	**Layer description**	**Thickness**	**Conductivity**	**Density**	**Heat Capacity**	**Dry water vapour resistance**
			[m]	[W/mK]	[kg/m^3]	[kJ/kgK]	[-]
	1	Concrete conglomerate	0.05	1.34	2200	1.05	34
	2	Pebbles and crushed stone	0.20	0.70	1500	1.00	5
	3	Ground	-	0.93	-	-	-

Table 22. Ground floor components thermo-physical features

Code	**Thickness**	**Surface mass**	**Thermal Transmittance**[1] (UNI EN ISO 6946)	**Thermal Transmittance**[2] (UNI EN ISO 13379)
	[m]	[kg/m^2]	[W/m^{2}K]	[W/m^{2}K]
G type floor: from conditioned room to ground				
P1	0.25	410	1.88	0.39

[1] The transmittance value is calculated considering only the slab thermal resistance.
[2] The transmittance value is calculated considering also the ground thermal resistance.

Building opaque envelope: roof

The roof thickness is 0.4 m and the absorption factor is assumed equal to 0.3 because of its light color. The roof stratigraphy and its materials thermo-physical features are reported in Table 23. Table 24 summarizes the main roof components thermo-physical features. The roof type identified in the model is the following:

- T type roof separates conditioned room from external

Table 23. Roof stratigraphy and materials thermo-physical features

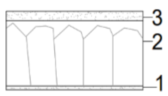
Stratigraphy	**N.**	**Layer description**	**Thickness**	**Conductivity**	**Density**	**Heat Capacity**	**Dry water vapour resistance**
			[m]	[W/mK]	[kg/m^3]	[kJ/kgK]	[-]
	1	Tuff and lime	0.02	0.80	1600	1	10
	2	Stone roof	0.40	0.81	2000	0.84	50
	3	Lime and sand plaster	0.05	0.80	1600	1	10

Table 24. Roof components thermo-physical features

Code	Thickness	Surface mass	Thermal Transmittance
	[m]	[kg/m^2]	[W/m^{2}K]
T type roof: from conditioned room to external			
S1	0.40	660	1.52

Thermographic visualisation of building envelope

Figure 18 shows the thermographic visualization of the envelope components. Excluding windows, the vaulted roofs present the highest thermal transmittance values. Conversely, the external thickest walls are characterized by the lowest thermal transmittance values.

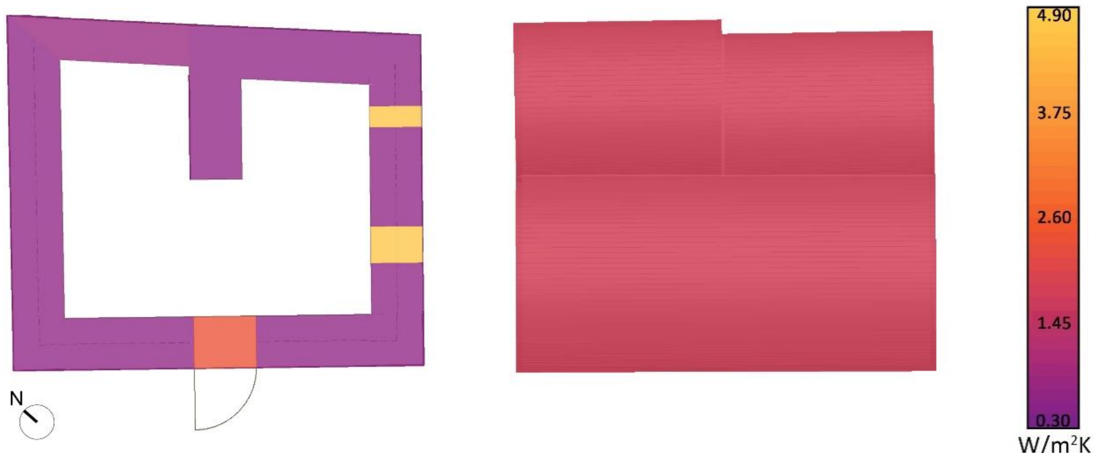


Figure 18. Building and roof plan - thermographic visualisation

BUILDING SYSTEMS

Space heating and space cooling system

The space heating is provided by an electric heater. Emission, regulation and distribution subsystems efficiency values are assumed approximately equal to 100% in order to simulate in the model this type of generator. Heating system seasonal generation efficiencies, calculated according to UNI/TS 11300-2:2019, are reported in Table 25.

Table 25. Space heating system generation efficiencies

Seasonal generation efficiency $\eta_{H.gen.ut}$	Seasonal generation efficiency referred to primary non-renewable energy $\eta_{H.gen.p.nren}$
[%]	[%]
100	51.3

The space cooling system is assumed as not present in the model of the *dammuso* archetype.

Domestic hot water production system

DHW production is provided by a hot water storage heater. Emission, regulation and distribution subsystems efficiencies are calculated according to UNI/TS 11300-2:2019. DHW production system seasonal generation efficiencies, calculated according to UNI/TS 11300-2:2019, are reported in Table 26.

Table 26. DHW production system generation efficiencies

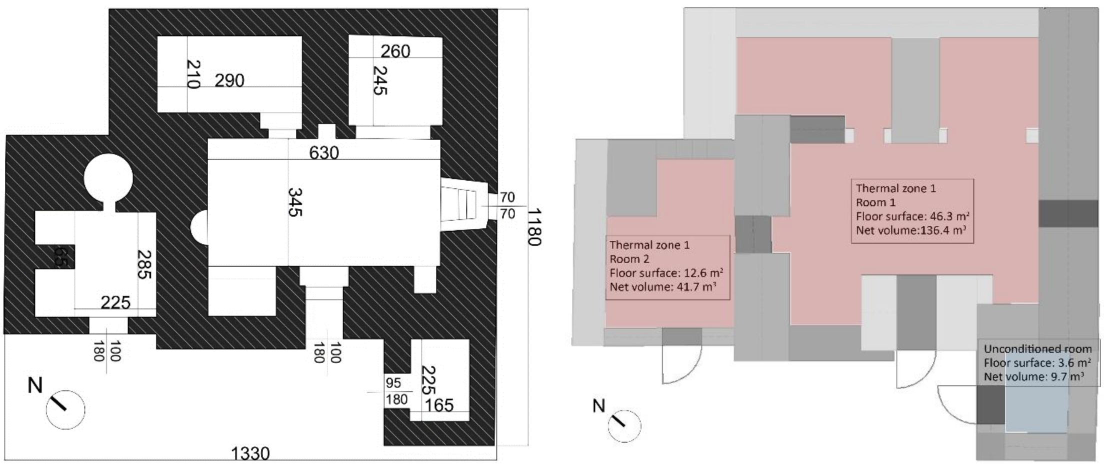
Seasonal generation efficiency $\eta_{W.gen.ut}$	**Seasonal generation efficiency referred to primary non-renewable energy** $\eta_{W.gen.p.nren}$
[%]	[%]
75	38.5

ARCHETYPE 2: *DAMMUSO PER AGGREGAZIONE COMPLESSA*

GEOMETRIC DATA

The case study is a 117 m^2 isolated *dammuso* located in Pantelleria. The building is characterized by one floor with, a conditioned net floor area of about 59 m^2 and a conditioned net volume of 178 m^3. The building is modeled through a single conditioned thermal zone. The small south facing room is considered as unconditioned space characterized by a net floor area of 3.6 m^2 and a conditioned net volume of about 10 m^3.

The archetype building plan and the thermal zones map are presented in Figure 19, while Table 27 lists the main geometric data of the building.



(a) *(b)*

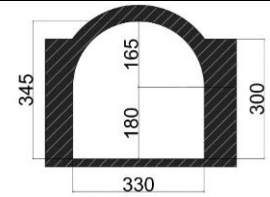
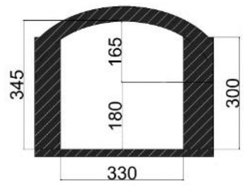
Figure 19. Dammuso plan (a) and dammuso model with thermal zone (b)

Table 27. Main geometric data

Net conditioned floor area	Gross conditioned floor area	Net conditioned volume	Gross conditioned volume	Building components area	Aspect ratio
[m^2]	[m^2]	[m^3]	[m^3]	[m^2]	[m^{-1}]
58.9	108.7	178.0	396.5	369.6	0.93

The same assumptions made for vaults modelling referred to Archetype 1 (see page 38) are considered. A comparison between the two sections is provided in Table 28 and Figure 20 shows a 3D view of the modeled building.

Table 28. Comparison between real and modeled section

Real section		**Modeled section**	
			
Room volume [m^3]	**Roof area** [m^2]	**Room volume** [m^3]	**Roof area** [m^2]
10.3	11.1	10.8	11.0

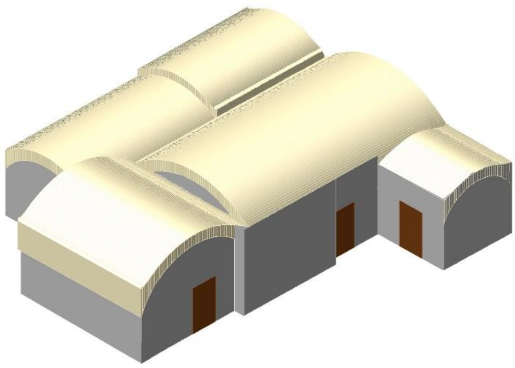


Figure 20. 3D view of the building

Table 29 reports the building components area according to the different orientation.

Table 29. Building components area divided according to orientation

Orientation	**Building components area** [m^2]				
	Walls	***Doors***	***Windows***	***Floor***	***Roof***
NE	43.0	-	-	-	51.9
SE	18.1	-	0.5	-	16.4
SW	27.7	3.6	-	-	50.8
NW	22.6	-	-	-	16.0
HOR	-	-	-	108.7	0.1

THERMO-PHYSICAL CHARACTERISTICS OF THE BUILDING ENVELOPE

The structure and the envelope of the typical *dammuso* are made by stone bearing walls. The vaulted roofs are made by stones. The ground floor is made by concrete conglomerate and is leaned on ground.

Wall components are identified by *M* code and number 1 to 16. Floor components are identified by *P* code and number 1-2. Roof components are identified by *S* code and number 1-2. Window is identified by code *W1* and door components are identified by *D* code and number 1-2. All the envelope components identification codes are provided in Figure 21.

The building envelope thermo-physical properties adopted in the model are mainly taken from the experimental measurements for a typical *dammuso* provided in Rodonò et al, 1980. The lime and sand plaster thermo-physical features are derived from UNI EN ISO 10456:2008.

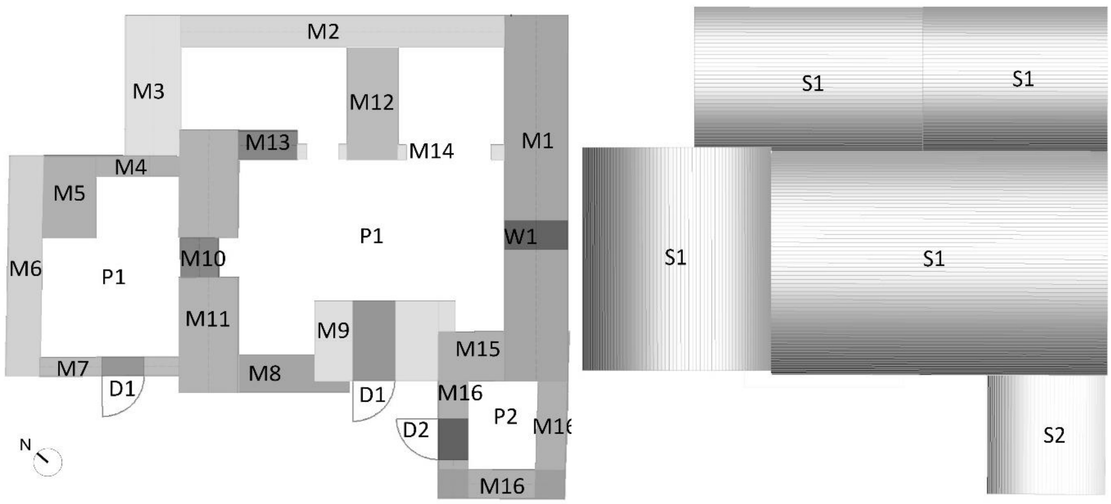


Figure 21. Building and roof plan - envelope components identification codes

Building opaque envelope: walls

The walls are characterized by different thicknesses and the absorption factor is assumed equal to 0.6. The wall stratigraphy and its materials average thermo-physical features are reported in Table 30. Table 31 summarizes the main wall components thermo-physical features. Four types of walls are identified in the model:

- T type wall separates conditioned room from external
- D type wall represents conditioned zone internal separation
- U type wall separates conditioned room from unconditioned room
- E type wall separates unconditioned room from external

Table 30. Wall stratigraphy and materials average thermo-physical features

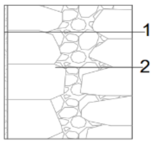
Stratigraphy	N	Layer description	Thickness	Conductivity	Density	Heat Capacity	Dry water vapour resistance
			[m]	[W/mK]	[kg/m^3]	[kJ/kgK]	[-]
	1	Lime and sand plaster	0.02	0.80	1600	1	10
	2	"Casciata" wall	1.00	0.81	2000	0.84	50

Table 31. Wall components thermo-physical features

Code	Thickness	Surface mass	Thermal Transmittance
	[m]	[kg/m^2]	[W/m^{2}K]
T type walls: from conditioned room to external			
M1	1.50	2960	0.49
M2	0.75	1460	0.90
M3	1.30	2560	0.56
M4	0.50	960	1.24
M5	2.00	3960	0.38
M6	0.80	1560	0.85
M7	0.45	860	1.34
M8	0.90	1760	0.77
M9	1.95	3860	0.39
D type walls: conditioned zone internal separation			
M10	0.90	1720	0.73
M11	1.40	2720	0.50
M12	1.20	2320	0.58
M13	0.70	1320	0.89
M14	0.35	620	1.45
U type walls: from conditioned room to unconditioned room			
M15	1.20	2320	0.58
E type walls: from unconditioned room to external			
M16	0.70	1360	0.95

Building opaque envelope: doors

The modeled door components are constituted by a wood panel. The doors materials thermo-physical features are derived from UNI 10351:2021 and are listed in Table 32. Door components thermo-physical features are reported in Table 33.

Table 32. Door materials thermo-physical features

Component	Description	Thickness	Thermal Resistance	Density	Heat Capacity
		[m]	[m²K/W]	[kg/m³]	[kJ/kgK]
	Pine wood: fiber perpendicular flow	0.03	0.21	550	1.6

Table 33. Door components thermo-physical features

Code	Thickness	Surface mass	Thermal Transmittance
	[m]	[kg/m²]	[W/m²K]
T type door: from conditioned room to external			
D1	0.03	17	2.45
E type door: from unconditioned room to external			
D2	0.03	17	2.45

Building transparent envelope: windows

The modeled window components are constituted by a single layer of glass and by a wood frame. The glass and frame transmittance values are provided by Annex B of the technical Standard UNI/TS 11300-1:2014. Windows transmittance values for climatic zone B are derived from Ballarini et al. (2017) and Corrado et al. (2014). Window components thermo-physical features are reported in Table 34.

Table 34. Window components thermo-physical features

Code	Description	Solar transmittance factor	Glass Thermal Transmittance	Frame Thermal Transmittance	Window Thermal Transmittance
		[-]	[W/m²K]	[W/m²K]	[W/m²K]
T type: from conditioned room to external					
W1	Single glass and wood frame window	0.85	5.7	1.6	4.9

Building opaque envelope: ground floor

The ground floor is assumed leaned on ground. The ground is characterized by a conductivity equal to 0.93 W/mK. The ground floor consists of a concrete conglomerate layer realized on a pebbles and crushed stone layer. The floor stratigraphy and its materials thermo-physical features are reported in Table 35. Table 36 summarizes the main thermo-physical features of the floor components. Two types of floors are identified in the model:

- G type floor separates conditioned room from ground
- D type floor separates unconditioned room from ground

Table 35. Ground floor stratigraphy and materials thermo-physical features

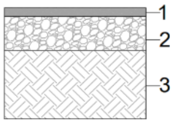
Stratigraphy	**N**	**Layer description**	**Thickness**	**Conductivity**	**Density**	**Heat Capacity**	**Dry water vapour resistance**
			[m]	[W/mK]	[kg/m^3]	[kJ/kgK]	[-]
	1	Concrete conglomerate	0.05	1.34	2200	1.05	34
	2	Pebbles and crushed stone	0.20	0.70	1500	1.00	5
	3	Ground	-	0.93	-	-	-

Table 36. Ground floor components thermo-physical features

Code	**Thickness**	**Surface mass**	**Thermal Transmittance**[1] (UNI EN ISO 6946)	**Thermal Transmittance**[2] (UNI EN ISO 13379)
	[m]	[kg/m^2]	[W/m^{2}K]	[W/m^{2}K]
G type floor: from conditioned room to ground				
P1	0.25	410	1.88	0.35
R type floor: from unconditioned room to ground				
P2	0.25	410	1.88	0.42

[1] The transmittance value is calculated considering only the slab thermal resistance.
[2] The transmittance value is calculated considering also the ground thermal resistance.

Building opaque envelope: roof

The roof thickness is 0.4 m and the absorption factor is assumed equal to 0.3 because of its light color. The roof stratigraphy and its materials thermo-physical features are reported in Table 37. Table 38 summarizes the main roof components thermo-physical features. Two types of roofs are identified in the model:

- T type roof separates conditioned room from external
- E type roof separates unconditioned room from external

Table 37. Roof stratigraphy and materials thermo-physical features

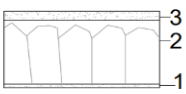
Stratigraphy	**N.**	**Layer description**	**Thickness**	**Conductivity**	**Density**	**Heat Capacity**	**Dry water vapour resistance**
			[m]	[W/mK]	[kg/m^3]	[kJ/kgK]	[-]
	1	Tuff and lime	0.02	0.80	1600	1	10
	2	Stone roof	0.40	0.81	2000	0.84	50
	3	Lime and sand plaster	0.05	0.80	1600	1	10

Table 38. Roof components thermo-physical features

Code	Thickness	Surface mass	Thermal Transmittance
	[m]	[kg/m²]	[W/m²K]
T type roof: from conditioned room to external			
S1	0.40	660	1.52
E type roof: from unconditioned room to external			
S2	0.40	660	1.52

Thermographic visualisation of building envelope

Figure 22 shows the thermographic visualisation of the envelope components. Excluding window, the vaulted roofs present the highest thermal transmittance values. Conversely, the external thickest walls are characterized by the lowest thermal transmittance values.

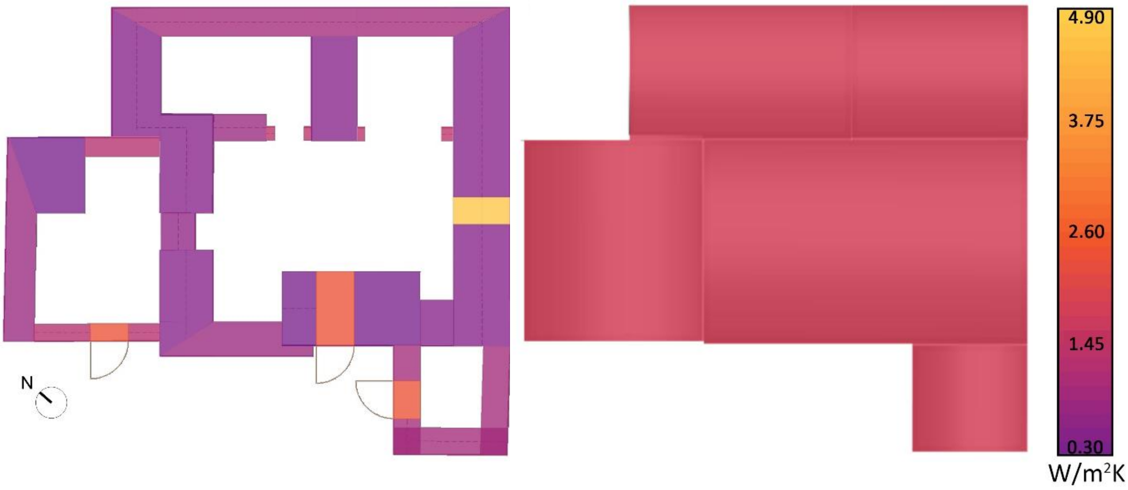


Figure 22. Building and roof plan - thermographic visualisation

BUILDING SYSTEMS

Space heating and space cooling system

The space heating is provided by an electric heater. Emission, regulation and distribution subsystems efficiency values are assumed approximately equal to 100% in order to simulate in the model this type of generator. Heating system seasonal generation efficiencies, calculated according to UNI/TS 1300-2:2019, are reported in Table 39.

Table 39. Space heating system generation efficiencies

Seasonal generation efficiency $\eta_{H.gen.ut}$	Seasonal generation efficiency referred to primary non-renewable energy $\eta_{H.gen.p.nren}$
[%]	[%]
100	51.3

The space cooling system is assumed as not present in the model of the *dammuso* archetype.

Domestic hot water production system

DHW production is provided by a hot water storage heater. Emission, regulation and distribution subsystems efficiencies are calculated according to UNI/TS 1300-2:2019. DHW production system seasonal generation efficiencies, calculated according to UNI/TS 1300-2:2019, are reported in Table 40.

Table 40. DHW production system generation efficiencies

Seasonal generation efficiency $\eta_{W.gen.ut}$	**Seasonal generation efficiency referred to primary non-renewable energy** $\eta_{W.gen.p.nren}$
[%]	[%]
75	38.5

ARCHETYPE 3: *DAMMUSO PER AGGREGAZIONE COMPLESSA CON ELEMENTI ACCESSORI E PERTINENZE*

GEOMETRIC DATA

The case study is a 154 m^2 isolated *dammuso* located in Pantelleria. The building is characterized by one floor with, a conditioned net floor area of about 97 m^2 and a conditioned net volume of 310 m^3. The building is modeled through two conditioned thermal zones. The archetype building plan and the thermal zones map are presented in Figure 23, while Table 41 lists the main geometric data of the building.

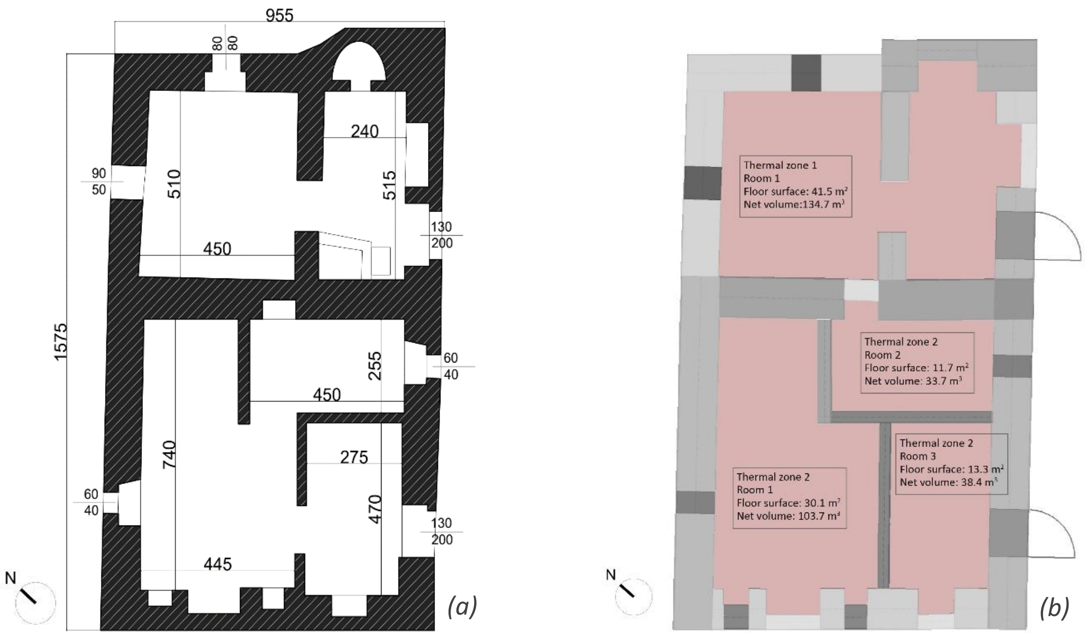


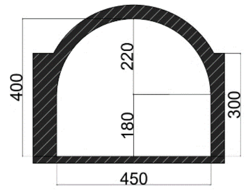
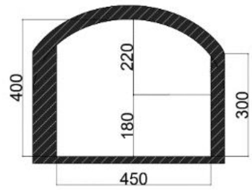
Figure 23. Dammuso plan (a) and dammuso model with thermal zone (b)

Table 41. Main geometric data

Net conditioned floor area	**Gross conditioned floor area**	**Net conditioned volume**	**Gross conditioned volume**	**Building components area**	**Aspect ratio**
[m^2]	[m^2]	[m^3]	[m^3]	[m^2]	[m^{-1}]
96.6	153.5	310.5	588.3	520.2	0.88

The same assumptions made for vaults modelling referred to Archetype 1 (see page 38) are considered. A comparison between the two sections is provided in Table 42 and Figure 24 shows a 3D view of the modeled building.

Table 42. Comparison between real and modeled section

Real section		**Modeled section**	
			
Room volume [m^3]	**Roof area** [m^2]	**Room volume** [m^3]	**Roof area** [m^2]
79.6	29.2	85.7	28.0

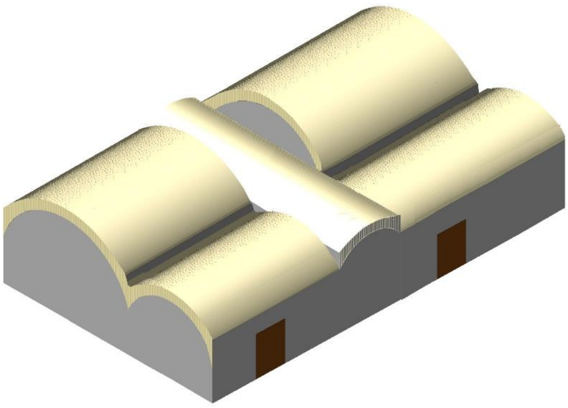


Figure 24. 3D view of the building

Table 43 reports the building components area according to the different orientation.

Table 43. Building components area divided according to orientation

Orientation	**Building components area** [m^2]				
	Walls	***Doors***	***Windows***	***Floor***	***Roof***
NE	29.5	-	0.6	-	20.0
SE	51.0	4.7	0.3	-	77.8
SW	24.2	-	-	-	21.4
NW	57.8	-	0.7	-	77.9
HOR	-	-	-	153.5	0.9

THERMO-PHYSICAL CHARACTERISTICS OF THE BUILDING ENVELOPE

The structure and the envelope of the typical *dammuso* are made by stone bearing walls. The vaulted roofs are made by stones. The ground floor is made by concrete conglomerate and is leaned on ground.

Wall components are identified by *M* code and number 1 to 12. Floor components are identified by code *P1*. Roof components are identified by code *S1*. Window components are identified by *W* code and number 1 to 3 and door components are identified by code *D1*. All the envelope components identification codes are provided in Figure 25.

The building envelope thermo-physical properties adopted in the model are mainly taken from the experimental measurements for a typical *dammuso* provided in Rodonò et al. (1980). The lime and sand plaster thermo-physical features are derived from UNI EN ISO 10456:2008.

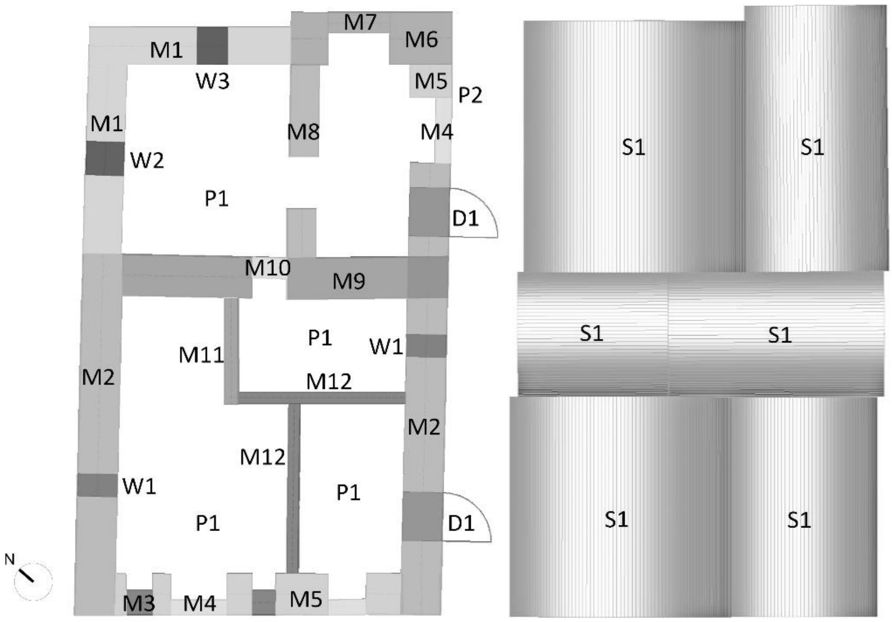


Figure 25. Building and roof plan - envelope components identification codes

Building opaque envelope: walls

The walls are characterized by different thicknesses and the absorption factor is assumed equal to 0.6. The wall stratigraphy and its materials average thermo-physical features are reported in Table 44. Table 45 summarizes the main wall components thermo-physical features. Two types of walls are identified in the model:

- T type wall separates conditioned room from external
- D type wall represents conditioned zone internal separation

Table 44. Wall stratigraphy and materials average thermo-physical features

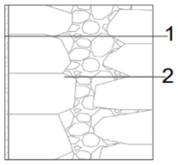
Stratigraphy	N	Layer description	Thickness	Conductivity	Density	Heat Capacity	Dry water vapour resistance
			[m]	[W/mK]	[kg/m³]	[kJ/kgK]	[-]
	1	Lime and sand plaster	0.02	0.80	1600	1	10
	2	"Casciata" wall	0.80	0.81	2000	0.84	50

Table 45. Wall components thermo-physical features

Code	Thickness	Surface mass	Thermal Transmittance
	[m]	[kg/m²]	[W/m²K]
T type walls: from conditioned room to external			
M1	1.00	1960	0.70
M2	1.05	2060	0.67
M3	0.65	1260	1.00
M4	0.40	760	1.46
M5	1.10	2160	0.65
M6	1.40	2760	0.52
M7	0.55	1060	1.15
D type walls: conditioned zone internal separation			
M8	0.75	1420	0.85
M9	1.10	2120	0.62
M10	0.55	1020	1.07
M11	0.35	620	1.45
M12	0.30	520	1.59

Building opaque envelope: doors

The modeled door components are constituted by a wood panel. The doors materials thermo-physical features are derived from UNI 10351:2021 and are listed in Table 46. Door components thermo-physical features are reported in Table 47.

Table 46.Door materials thermo-physical features

Component	Description	Thickness	Thermal Resistance	Density	Heat Capacity
		[m]	[m²K/W]	[kg/m³]	[kJ/kgK]
	Pine wood: fiber perpendicular flow	0.03	0.21	550	1.6

Table 47. Door components thermo-physical features

Code	Thickness	Surface mass	Thermal Transmittance
	[m]	[kg/m^2]	[W/m^{2}K]
T type door: from conditioned room to external			
D1	0.03	17	2.45

Building transparent envelope: windows

The modeled window components are constituted by a single layer of glass and by a wood frame. The glass and frame transmittance values are provided by Annex B of the technical Standard UNI/TS 11300-1:2014. Windows transmittance values for climatic zone B are derived from Ballarini et al. (2017) and Corrado et al. (2014). Window components thermo-physical features are reported in Table 48.

Table 48. Window components thermo-physical features

Code	Description	Solar transmittance factor	Glass Thermal Transmittance	Frame Thermal Transmittance	Window Thermal Transmittance
		[-]	[W/m^{2}K]	[W/m^{2}K]	[W/m^{2}K]
T type: from conditioned room to external					
W1	Single glass and wood frame window	0.85	5.7	1.6	4.9
W2	Single glass and wood frame window	0.85	5.7	1.6	4.9
W3	Single glass and wood frame window	0.85	5.7	1.6	4.9

Building opaque envelope: ground floor

The ground floor is assumed leaned on ground. The ground is characterized by a conductivity equal to 0.93 W/mK. The ground floor consists of a concrete conglomerate layer realized on a pebbles and crushed stone layer. The floor stratigraphy and its materials thermo-physical features are reported in Table 49. Table 50 summarizes the main thermo-physical features of the floor components.

The floor type identified in the model is the following:

- G type floor separates conditioned room from ground

Table 49. Ground floor stratigraphy and materials thermo-physical features

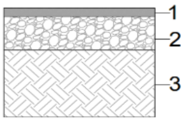
Stratigraphy	N	Layer description	Thickness	Conductivity	Density	Heat Capacity	Dry water vapour resistance
			[m]	[W/mK]	[kg/m^3]	[kJ/kgK]	[-]
	1	Concrete conglomerate	0.05	1.34	2200	1.05	34
	2	Pebbles and crushed stone	0.20	0.70	1500	1.00	5
	3	Ground	-	0.93	-	-	-

Table 50. Ground floor components thermo-physical features

Code	Thickness	Surface mass	Thermal Transmittance[1] (UNI EN ISO 6946)	Thermal Transmittance[2] (UNI EN ISO 13379)
	[m]	[kg/m^2]	[W/m^{2}K]	[W/m^{2}K]
G type floor: from conditioned room to ground				
P1	0.25	410	1.88	0.34

[1] The transmittance value is calculated considering only the slab thermal resistance.
[2] The transmittance value is calculated considering also the ground thermal resistance.

Building opaque envelope: roof

The roof thickness is 0.4 m and the absorption factor is assumed equal to 0.3 because of its light color. The roof stratigraphy and its materials thermo-physical features are reported in Table 51. Table 52 summarizes the main roof components thermo-physical features. The roof type identified in the model is the following:

- T type roof separates conditioned room from external

Table 51. Roof stratigraphy and materials thermo-physical features

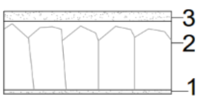
Stratigraphy	N.	Layer description	Thickness	Conductivity	Density	Heat Capacity	Dry water vapour resistance
			[m]	[W/mK]	[kg/m^3]	[kJ/kgK]	[-]
	1	Tuff and lime	0.02	0.80	1600	1	10
	2	Stone roof	0.40	0.81	2000	0.84	50
	3	Lime and sand plaster	0.05	0.80	1600	1	10

Table 52. Roof components thermo-physical features

Code	Thickness	Surface mass	Thermal Transmittance
	[m]	[kg/m^2]	[W/m^{2}K]
T type roof: from conditioned room to external			
S1	0.40	660	1.52

Thermographic visualisation of building envelope

Figure 26 shows the thermographic visualisation of the envelope components. Excluding window, the vaulted roofs present the highest thermal transmittance values. Conversely, the external thickest walls are characterized by the lowest thermal transmittance values.

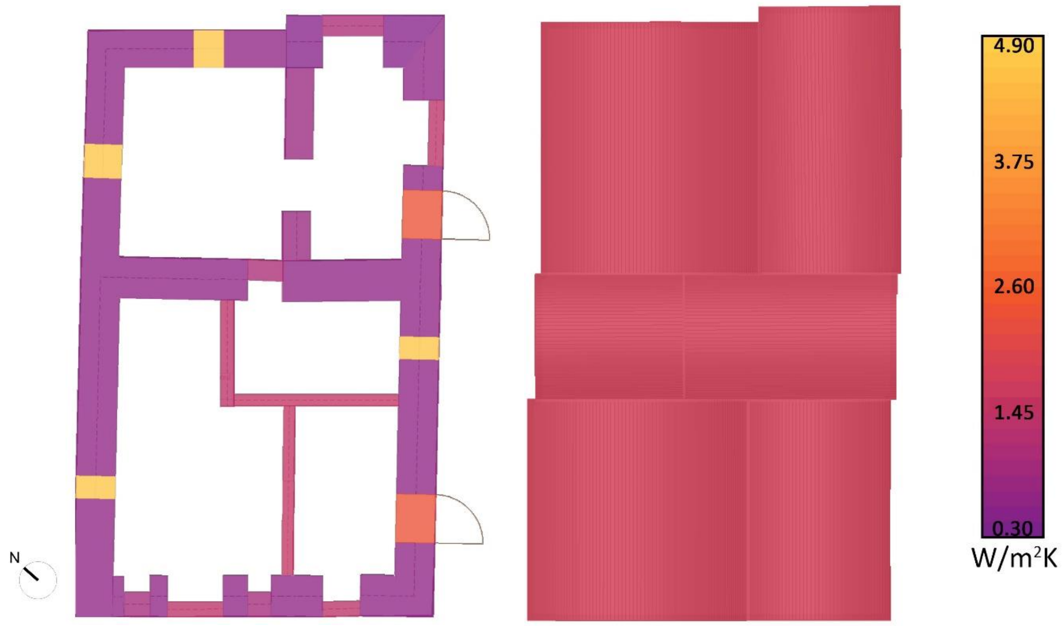


Figure 26. Building and roof plan - thermographic visualisation

BUILDING SYSTEMS

Space heating and space cooling system

The space heating is provided by an electric heater. Emission, regulation and distribution subsystems efficiency values are assumed approximately equal to 100% in order to simulate in the model this type of generator. Heating system seasonal generation efficiencies, calculated according to UNI/TS 1300-2:2019, are reported in Table 53.

Table 53. Space heating system generation efficiencies

Seasonal generation efficiency $\eta_{H.gen.ut}$	Seasonal generation efficiency referred to primary non-renewable energy $\eta_{H.gen.p.nren}$
[%]	[%]
100	51.3

The space cooling system is assumed as not present in the model of the *dammuso* archetype.

Domestic hot water production system

DHW production is provided by a hot water storage heater. Emission, regulation and distribution subsystems efficiencies are calculated according to UNI/TS 1300-2:2019. DHW production system seasonal generation efficiencies, calculated according to UNI/TS 1300-2:2019, are reported in Table 54.

Table 54. DHW production system generation efficiencies

Seasonal generation efficiency $\eta_{W.gen.ut}$	**Seasonal generation efficiency referred to primary non-renewable energy** $\eta_{W.gen.p.nren}$
[%]	[%]
75	38.5

5.2 Current state assessment of *dammusi* archetypes

Through the energy simulation of the three archetypes models, the energy performance of each *dammuso* archetype is quantitatively assessed in terms of:

- Energy needs: energy needs for space heating, space cooling and domestic hot water production;
- Annual energy consumptions: electricity and primary energy consumption;
- Annual CO_{2eq} emissions.

The subsequent sections describe the developed energy performance assessment and show the main outcomes achieved for the three *dammusi* archetypes, through a set of comparative bar charts.

BUILDING ENERGY NEEDS

ENERGY NEEDS FOR SPACE HEATING AND SPACE COOLING

Energy needs for space heating and cooling are calculated in compliance with UNI EN ISO 52016-1:2018 and UNI/TS 11300-1:2014.

Annual energy needs for space heating and space cooling for the archetypes models in the current state are shown in Figure 27.

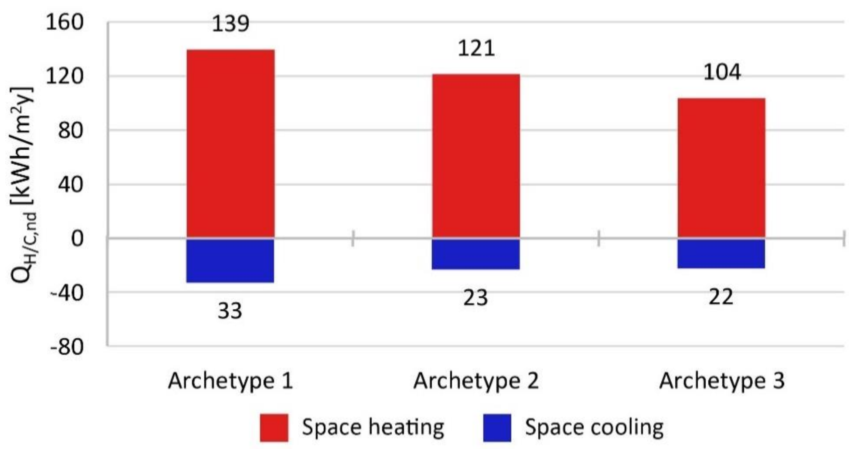


Figure 27. Annual energy needs for space heating and space cooling

ENERGY NEEDS FOR DOMESTIC HOT WATER

The annual energy need for DHW is calculated in compliance with UNI/TS 11300-2:2019. The estimated domestic hot water consumption is equal to 50 l/d for Archetype 1, 99 l/d for Archetype 2 and 162 l/d for Archetype 3.

Annual energy needs for DHW for the archetypes models in the current state are shown in Figure 28.

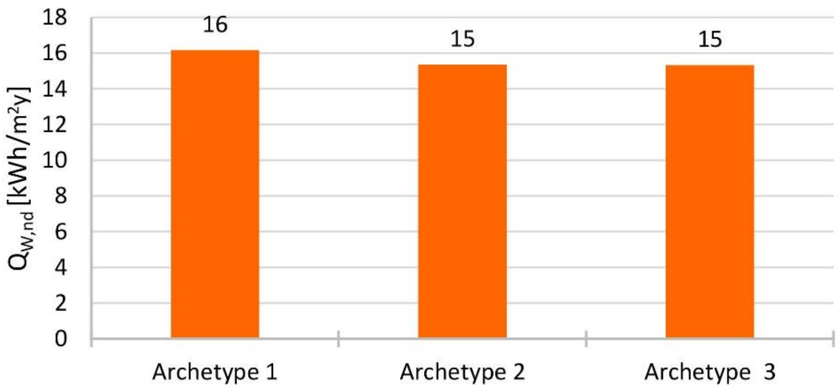


Figure 28. Annual energy needs for DHW

CONSUMPTIONS AND EMISSIONS

Electricity and primary energy consumptions for space heating and DHW are calculated in compliance with UNI/TS 11300-2:2019 and UNI/TS 11300-4:2016. Since no system for space cooling is present, space cooling consumptions are null. Electricity needs for lighting and equipment are not considered.

ELECTRICITY CONSUMPTIONS

Annual electricity consumptions for space heating and DHW for the archetypes models in the current state are reported in Figure 29. Since there are no systems for the exploitation of on-site renewable energy sources, the electricity consumed is entirely taken from the local power grid.

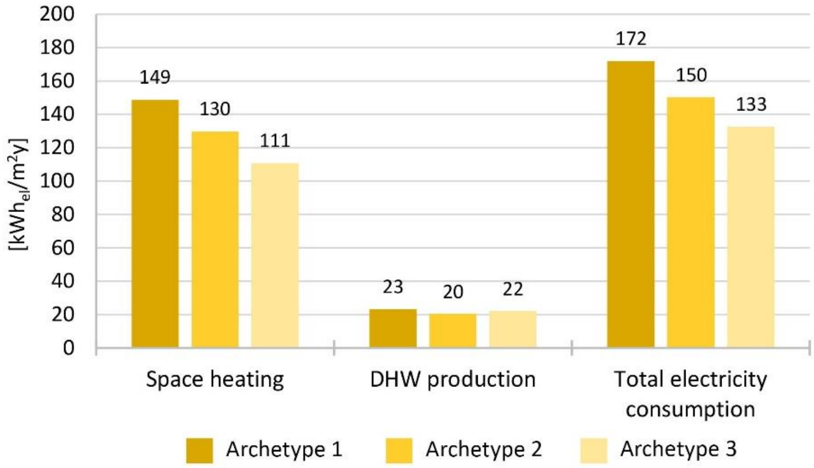


Figure 29. Annual electricity consumptions for space heating and DHW services

PRIMARY ENERGY CONSUMPTION AND EMISSIONS

Primary energy consumption is calculated using both national and local conversion factors for electricity; indeed, electricity supplied by local grid is produced from fossil fuels for a much higher share than the national one. As a consequence, primary energy consumption derived from electricity consumption is different and further analyzed. Table 55 reports electricity conversion factors to primary energy. In addition, CO_{2eq} emission factor is reported in the last column of the table.

Table 55. Conversion factors to primary energy and CO_{2eq} emission factor

ENERGY CARRIER	**PRIMARY ENERGY**						**CO_{2eq} EMISSIONS**
	Primary energy conversion factor (f_p)		***Non-renewable primary energy conversion factor ($f_{p,nren}$)***		***Renewable primary energy conversion factor ($f_{p,ren}$)***		**CO_{2eq} emission factor** (ENEA)
	National conversion factors (D.M. 26.6.2015)	**Local conversion factors** (S.Med.E)	**National conversion factors** (D.M. 26.6.2015)	**Local conversion factors** (S.Med.E)	**National conversion factors** (D.M. 26.6.2015)	**Local conversion factors** (S.Med.E)	
ELECTRICITY	2.42	3.03	1.95	3.09 (97.15% of energy produced, 2021)	0.47	1.14 (2.85% of energy produced, 2021)	0.46

Figure 30 shows annual primary energy consumptions calculated with both national and local conversion factors subdivided into renewable primary energy and non-renewable primary energy for the archetypes models in the current state.

Figure 31 shows total annual primary energy consumption calculated with both national and local conversion factors.

By comparing Figure 30 and Figure 31, it is noticeable that total primary energy consumption is about equal to non-renewable primary energy consumption when local conversion factors are used. Indeed, according to "*Piano D'Azione per l'Energia Sostenibile del Comune di Pantelleria (2015)*" energy is mainly produced by non-renewable sources, which, therefore, most affect total primary energy consumption.

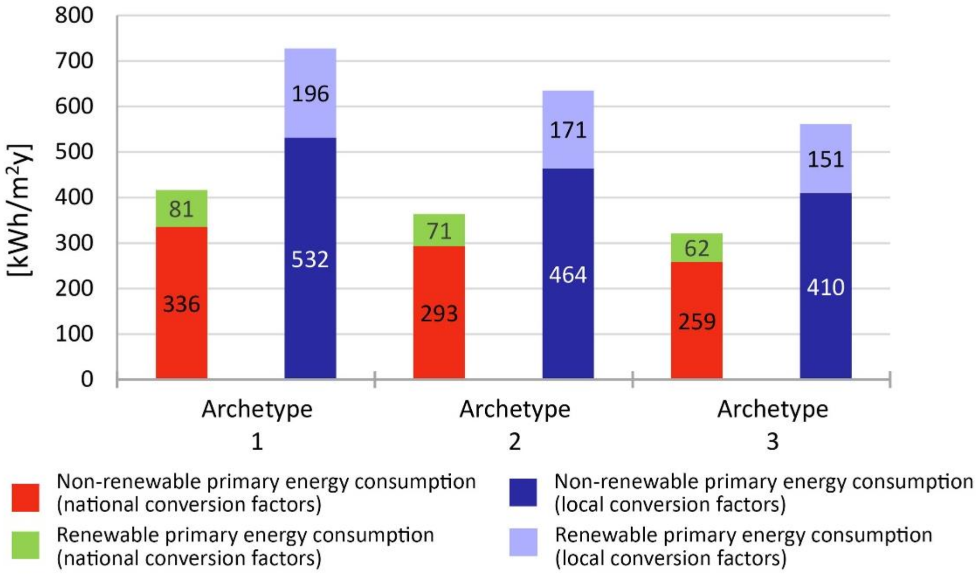


Figure 30. Annual primary energy consumption subdivided into renewable and non-renewable energy consumption

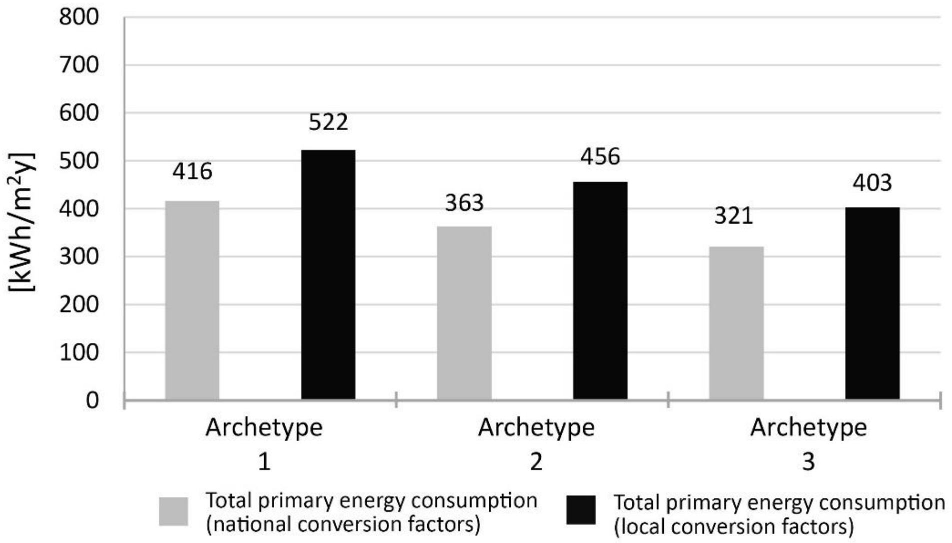


Figure 31. Total annual primary energy consumption

Annual CO_{2eq} emissions for the archetypes models in the current state are shown in Figure 32.

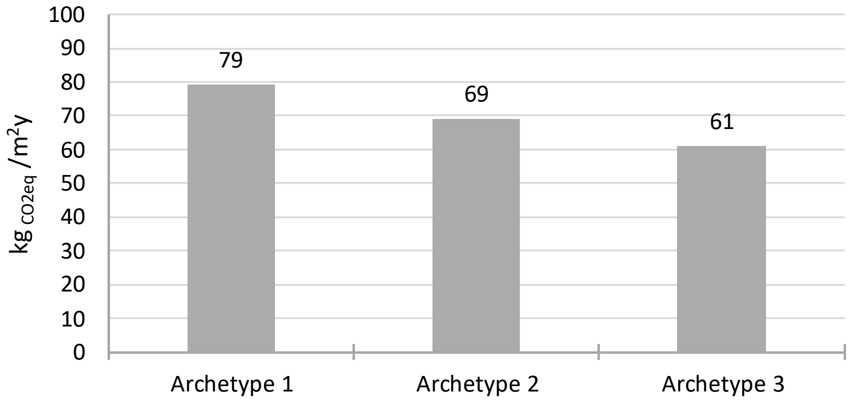


Figure 32. Annual CO_{2eq} emissions

5.2.1 Results discussion

Analyzing the energy performance results for the three *dammusi* building archetypes in the current state, some general outcomes can be drawn to provide the basis for setting out the alternative strategies for their energy retrofit, with a view to both decarbonization and robustness and resilience enhancement.

In the first instance, current state envelope performance results show that the average thermal transmittance values of opaque envelope components (i.e., walls, roofs, and doors) and transparent envelope components (i.e., windows) are higher than the limit values set for climatic zone B by DM 26.06.2015. This implies high building energy needs, especially for space heating, which in turn result in high energy consumptions. Energy needs for space cooling, instead, are quite low and, since no systems for space cooling are present, energy consumption for space cooling is not considered.

Besides bringing higher energy needs, high envelope transmittance values make buildings not robust and resilient. According to different studies, as pointed out in Chapter 2, a well performing envelope can provide a higher robustness level to stand to climate change effects (e.g., increasing external temperatures) than a bad performing envelope. Furthermore, a well performing envelope can improve building resilience against unexpected power outages due to extreme events, assuring more acceptable thermal comfort conditions in case of building systems interruptions than less performing envelopes (characterized by higher transmission losses). Therefore, since Pantelleria Island may be affected by the consequences of climate change in the future, such as rising external temperatures and increasing frequency of disruptive events, the implementation of interventions on *dammusi* buildings envelope can bring various advantages under different point of view.

In the second place, as regards *dammusi* building systems for space heating and DHW production, it can be concluded that the existing systems are not efficient, thereby implying high final consumptions. Indeed, space heating is mainly provided by electric heaters and DHW is mainly produced using electric hot water storage heaters. Since they are electricity-based systems, they should contribute to building overall robustness and resilience, as state by different studies deepened in Chapter 2. However, because of their inefficiency, existing systems are highly sensible to occupants, whose principal requirement is thermal comfort, and, thus, may not guarantee building robustness to occupants' behaviour. Furthermore, existing systems, because of their inefficiency, demand a higher quantity of electricity, which is taken entirely form the local grid. In case of unexpected events, such as power outages due to extreme events or caused by a congestion of the unstable local power grid, existing systems may not be able to guarantee normal building services, making the building not resilient. This is further worsened by the complete absence of on-site renewable energy sources (as PV) or batteries. According to the specific studies analysed in Chapter 2, on-site renewable energy sources allow making buildings more robust in terms of GHG emissions (especially in countries where the carbon intensity of the electricity grid mix is significantly higher) and increasing their energy self-sufficiency, thus rendering them more resilient against possible power outages. In addition, the introduction of battery electricity storage can further improve systems resilience, in case of power temporary failures. Since Pantelleria Island power grid is unstable and characterized by a high carbon intensity, the replacement of existing systems with more efficient ones coupled with the exploitation of on-site renewable energy sources and battery electricity storage, can reduce *dammusi* buildings energy consumptions and emissions. Furthermore, these solutions, could enhance *dammusi* robustness and resilience against various foreseeable and unforeseeable uncertainties (decarbonization of local electricity grid mix, power grid outages, increase of electricity demand due to occupants' requirements).

In conclusion, appropriate solutions for the retrofit of the *dammusi* buildings, involving interventions on building envelope, energy systems and integration of renewable sources, can be identified in order to meet both decarbonization goals and robustness and resilience requirements, in line with the challenges of future buildings.

5.3 Definition and modelling of energy retrofit strategies

The analysis of the current energy performance results provides the basis to set out energy retrofit scenarios analysis for *dammusi* buildings. Starting from the identification of various energy efficiency measures for *dammusi* buildings, involving building envelope, energy systems and renewable energy sources integration, the work aims to define and model diverse energy retrofit scenarios, combining the single measures identified.

5.3.1 Definition of energy efficiency measures for *dammusi* energy retrofit

The energy efficiency measures proposed for the retrofit of *dammusi* buildings take into account the following objectives:

1. Decarbonization of Pantelleria Island building stock, within the overall Mitigation Strategy.
2. Enhancement of Pantelleria Island building stock robustness and resilience, within the overall Adaption Strategy.

In line with the three pillars set out by the European energy efficiency strategy for buildings, the energy efficiency measures defined for *dammusi* are therefore defined to:

- Reduce *dammusi* buildings energy demand through interventions on building envelope (BE);
- Increase energy efficiency through interventions on building systems (BS);
- Reduce *dammusi* buildings dependence from the energy grid through the integration of on-site renewable energy sources (RS).

Suitable energy efficiency measures for *dammusi* buildings are selected taking into consideration regulatory constraints of *dammusi* buildings components and indications provided by local actors, including *the Ente Parco Nazionale Isola di Pantelleria* (PNIP).

REDUCING ENERGY DEMAND THROUGH INTERVENTIONS ON BUILDING ENVELOPE

Analyzing current state envelope performance results, it appears that opaque envelope components (walls, roof, and doors) and transparent envelope components (windows) average thermal transmittance values do not meet thermal transmittance limit values defined for climatic zone B by DM 26.06.2015, Appendix B (since 2021). Therefore, proposed envelope energy efficiency measures are mainly intended to insulate building opaque envelope (walls and roof) and replace windows and doors. No intervention on building envelope is expected only if current state envelope shows a good state of conservation.

Energy efficiency measures overview

Different envelope energy efficiency measures are provided according to different current state envelope features of *dammusi* buildings observed on Pantelleria Island: buildings with stone façade and buildings with plastered façade. Current state model for buildings with stone façade is identified by code CS0, while current state model for buildings with plastered façade is identified by code CS00. Considering regulatory constraints on building envelope, six envelope energy efficiency measures (BE) are defined. Measures BE1 and BE2 are referred to buildings with stone façade; measure from BE3 to BE6 are referred to buildings with plastered facade. Maintaining envelope at the current state is also a possibility when it shows a good state of conservation. Envelope energy efficiency measures are described below.

BE1

Interventions involving envelope provided in BE1 measure are the following:

- Innovative insulating plaster on internal surface of the walls;
- Windows and doors replacement;
- Innovative insulating plaster on internal surface of vault.

BE2

Interventions involving envelope provided in BE2 measure are the following:

- Traditional insulating plaster on internal surface of the walls;
- Windows and doors replacement;
- Traditional insulating plaster on internal surface of vault.

BE3

Interventions involving envelope provided in BE3 measure are the following:

- Innovative insulating plaster on external surface of the walls;
- Windows and doors replacement.

BE4

Interventions involving envelope provided in BE4 measure are the following:

- Traditional insulating plaster on external surface of the walls;
- Windows and doors replacement.

BE5

Interventions involving envelope provided in BE5 measure are the following:

- Traditional insulating plaster on internal surface of the walls;
- Traditional insulating plaster on external surface of the walls;

- Windows and doors replacement;
- Traditional insulating plaster on internal surface of vault.

BE6

Interventions involving envelope provided in BE6 measure are the following:
- Innovative insulating plaster on internal surface of the walls;
- Traditional insulating plaster on external surface of the walls;
- Windows and doors replacement;
- Innovative insulating plaster on internal surface of vault.

THERMO-PHYSICAL FEATURES OF BUILDING ENVELOPE

For each *dammuso* archetype, interventions on the existing envelope intend to involve the following envelope components:
- Walls;
- Doors;
- Windows;
- Roof.

Inferior slab is affected by no interventions and maintains previous thermo-physical features. *Cannizzato* is assumed to be present in all the existing *dammusi* building models.

Building opaque envelope: walls

Buildings with stone façade walls (CS0) are characterized by internal plaster and absorption factor is assumed equal to 0.6. Buildings with plastered façade walls (CS00) are characterized by internal and external plaster and absorption factor is assumed equal to 0.3. Insulating plaster added to internal and/or external surfaces of walls can be innovative insulating plaster or traditional insulating plaster. Materials thermo-physical features are derived from product data sheets. Table 56 summarizes innovative insulating plaster thermo-physical features and Table 57 summarizes traditional insulating plaster thermo-physical features.

Table 56. Innovative insulating plaster thermo-physical features

Layer description	Thickness	Conductivity	Density	Heat Capacity	Dry water vapour resistance
	[m]	[W/mK]	[kg/m^3]	[kJ/kgK]	[-]
Innovative nanocomposite plaster	0.004	0.0019	277	1	10

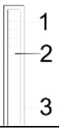
Table 57. Traditional insulating plaster thermo-physical features

Layer description	Thickness	Conductivity	Density	Heat Capacity	Dry water vapour resistance
	[m]	[W/mK]	[kg/m^3]	[kJ/kgK]	[-]
Natural mineral lime-based plaster	0.03	0.059	450	1	10

Building opaque envelope: doors

New door components are constituted by wood panels with a layer of air. The doors materials thermo-physical features are derived from UNI 10351:2021. Table 58 lists the door materials thermo-physical features.

Table 58. Doors materials thermo-physical features

Stratigraphy	N	Layer description	Thickness	Conductivity	Density	Heat Capacity
			[m]	[W/mK]	[kg/m^3]	[kJ/kgK]
	1	Pine wood	0.01	0.14	550	1.6
	2	Air layer	0.03	0.17	-	-
	3	Pine wood	0.01	0.14	550	1.6

Building transparent envelope: windows

New window components are constituted by a low-e double glazing filled with air (4.8.4) and by a wood frame. The glass and frame thermal transmittance values are provided by Annex B of the technical Standard UNI/TS 11300-1:2014. New windows are equipped with integrated wooden internal shutters. Additional thermal resistance of shutters is provided by Annex G of technical Standard UNI EN ISO 10077-1:2017 and UNI/TS 11300-1:2014. Windows transmittance values for climatic zone B are derived from Ballarini et al. (2017) and Corrado et al. (2014). Window components thermo-physical features are reported in Table 59.

Table 59. Windows components thermo-physical features

Description	Solar transmittance factor	Glass Thermal Transmittance	Frame Thermal Transmittance	Window Thermal Transmittance	Additional thermal resistance of shutters
	[-]	[W/m^{2}K]	[W/m^{2}K]	[W/m^{2}K]	[m^{2}K/W]
Low-e double glazing filled with air (4.8.4) + internal integrated shutters	0.67	2.2	2.0	2.3	0.22

Building opaque envelope: roof

Insulating plaster added to internal surface of vault can be innovative insulating plaster or traditional insulating plaster. Materials thermo-physical features are derived from product data sheets. Table 60 summarizes innovative insulating plaster thermo-physical features and Table 61 summarizes traditional insulating plaster thermo-physical features.

Table 60. Innovative insulating plaster thermo-physical features

Layer description	Thickness	Conductivity	Density	Heat Capacity	Dry water vapour resistance
	[m]	[W/mK]	[kg/m^3]	[kJ/kgK]	[-]
Innovative nanocomposite plaster	0.005	0.0019	277	1	10

Table 61. Traditional insulating plaster thermo-physical features

Layer description	Thickness	Conductivity	Density	Heat Capacity	Dry water vapour resistance
	[m]	[W/mK]	[kg/m^3]	[kJ/kgK]	[-]
Natural mineral lime-based plaster	0.03	0.059	450	1	10

INCREASING ENERGY EFFICIENCY THROUGH INTERVENTIONS ON BUILDING SYSTEMS

Analyzing *dammusi* building current state, it appears that systems for space heating and space cooling are almost never present. Space heating is mainly provided by electric heaters and DHW production is mainly provided by electric hot water storage heaters as evidenced by "*Piano D'Azione per l'Energia Sostenibile del Comune di Pantelleria* (2015)". Therefore, systems energy efficiency measures expect to:

1. Introduce new systems for space heating and space cooling;
2. Introduce a new system for domestic hot water production or maintain the existing working system.

ENERGY EFFICIENCY MEASURES OVERVIEW

Different building systems energy efficiency measures (BS) are defined according to the *dammusi* buildings occupancy types observed on Pantelleria island: "continuous" for permanent houses and "occasional" for summer holiday houses.

Eight systems energy efficiency measures are proposed considering different final uses combination. Measures from BS1 to BS6 are referred to buildings with continuous occupancy; measure from BE7 to BE9 are referred to buildings with occasional occupancy. Systems energy efficiency measures are described below.

BS1

It provides combined space heating and DHW production services. System generator is an air-to-water heat pump. Low temperature radiators are proposed as terminal devices for space heating and a thermal storage for DHW is present.

BS2

It provides combined space heating and DHW production services. System generator is a biomass boiler. High temperature radiators are proposed as terminal devices for space heating and a thermal storage for DHW is present.

BS3

It provides space heating and space cooling through a multi-split heat pump. DHW production is provided by the existing hot water storage heater.

BS4

It provides space heating and space cooling through a multi-split heat pump. DHW production is provided by a heat pump water heater with thermal storage.

BS5

It provides combined space heating, space cooling and DHW production services. System generator is a reversible air-to-water heat pump. Radiant floor panels are proposed as terminal devices for space heating and space cooling; a thermal storage for DHW is present.

BS6

Space heating and space cooling services are not provided. DHW production is provided by a heat pump water heater with thermal storage.

BS7

It provides only space cooling through a multi-split heat pump. DHW production is provided by the existing hot water storage heater.

BS8

It provides only space cooling through a multi-split heat pump. DHW production is provided by a heat pump water heater with thermal storage.

Some building systems solutions, which are described as potentially feasible by *Agenda per la Transizione Energetica dell’Isola di Pantelleria* (2020), such as ground source heat pumps, are not proposed. Indeed, until now, there are no application cases that can prove the actual cost-effectiveness resulting from ground source heat pumps installation. This matter can be deepened in the future.

BUILDING SYSTEMS FEATURES

The main features related to building systems implemented in the energy simulation software for all *dammusi* archetypes are reported. These include:

1. General system configuration (autonomous or combined systems);
2. Subsystems efficiency according to services provided (emission, regulation and distribution) assumed according to UNI/TS 1300-2:2019;
3. Generation features and efficiency.

Table 62, Table 63 and Table 64 list the main features related respectively to space heating systems, space cooling systems and domestic hot water production systems.

Table 62. Space heating systems features

EEM	GENERAL	SUBSYTEMS					GENERATION	
	System configuration	Terminal devices	Emiss. subsist. efficiency	Regulat. subsist. efficiency	Distrib. subsist. efficiency	Water supply temp.	Generator type	Generator efficiency/ COP
			[%]	[%]	[%]	[°C]		[-]
CS0 - CS00	Autonomous	-	-	94	99.5	70	Electric heater	1
BS1	Combined	Low temperature radiators	93	93	98.4	45	Air-to-water heat pump	1.86 ÷5.84
BS2	Combined	High temperature radiators	92	93	97.7	70	Biomass boiler	0.5
BS3	Autonomous	Internal split units	95	94	98.3	-	Reversible air-to-water heat pump	1.98÷4.6
BS4	Autonomous	Internal split units	95	94	98.3	-	Reversible air-to-water heat pump	1.98÷4.6
BS5	Combined	Radiant floor panels	96	91	98.7	35	Reversible air-to-water heat pump	1.86÷5.84

Table 63. Space cooling systems features

EEM	GENERAL	SUBSYSTEMS					GENERATION	
	System configuration	Terminal devices	Emission subsystem efficiency	Regulation subsystem efficiency	Distribution subsystem efficiency	Water supply temp.	Generator type	Generator efficiency/ EER
			[%]	[%]	[%]	[°C]		[-]
BS3	Autonomous	Internal split units	97	94	98	-	Reversible air-to-water heat pump	4.02
BS4	Autonomous	Internal split units	97	94	98	-	Reversible air-to-water heat pump	4.02
BS5	Combined	Radiant floor panels	97	93	98	19	Reversible air-to-water heat pump	3.68
BS7	Autonomous	Internal split units	97	94	98	-	Air-to-water heat pump	4.02
BS8	Autonomous	Internal split units	97	94	98	-	Air-to-water heat pump	4.02

Table 64. DHW systems features

EEM	GENERAL	SUBSYTEMS			GENERATION		STORAGE
	System configuratio n	Emission subsystem efficiency	Distribution subsystem efficiency	Water supply temperature	Generator type	Eventual generator performance	Thermal storage presence
		[%]	[%]	[°C]		[-]	
CS0-CS00	Autonomous	100	92.6	40	Hot water storage heater	-	No
BS1	Combined	100	92.6	40	Air-to-water heat pump	1.86÷5.84	Yes
BS2	Combined	100	92.6	40	Biomass boiler	-	No
BS3	Autonomous	100	92.6	40	Hot water storage heater	-	No
BS4	Autonomous	100	92.6	40	Heat pump water heater	3.07÷5.44	Yes
BS5	Combined	100	92.6	40	Reversible air-to-water heat pump	1.86÷5.84	Yes
BS6	Autonomous	100	92.6	40	Heat pump water heater	3.07÷5.44	Yes
BS7	Autonomous	100	92.6	40	Hot water storage heater	-	No
BS8	Autonomous	100	92.6	40	Heat pump water heater	3.07÷5.44	Yes

INTEGRATING ON-SITE RENEWABLE ENERGY SOURCES

Currently, electricity energy carrier meets most building energy needs. However, buildings are not electrically self-sufficient and local power grid largely depends for its energy supply from diesel systems as evidenced by "*Piano D'Azione per l'Energia Sostenibile del Comune di Pantelleria* (2015)". To implement the use of on-site renewable energy sources, the introduction of photovoltaic and solar thermal systems is proposed as energy efficiency strategy in order to increase buildings self-sufficiency and reduce dependency on fossil fuels.

ENERGY EFFICIENCY MEASURES OVERVIEW

Three energy efficiency measures related to renewable energy sources (RS) are proposed and are described below.

RS1

It introduces a photovoltaic system (PV) with battery electricity storage. Photovoltaic system is south-oriented and its electricity production is evaluated for three different slopes.

RS2

It introduces a photovoltaic system without battery electricity storage. Photovoltaic system is south-oriented and its electricity production is evaluated for three different slopes.

RS3

It introduces a solar thermal system with thermal storage. Solar thermal system is south-oriented with optimal slope.

The installation of a battery electricity storage is useful to cope with instability of local power grid. In addition, it allows to accumulate the energy produced in excess in order to use it when solar energy is not available.

RENEWABLE ENERGY SOURCES

Photovoltaic system

According to existing regulatory constraints, it is not allowed to install photovoltaic panels or solar thermal panels on *dammusi* roofs. Therefore, photovoltaic systems can be installed on ground, on secondary structures, such as pergolas or carports, or on *cannizzati*, which, in this regard, are not subject to constraints. On the basis of these assumptions, South oriented photovoltaic system electricity production is evaluated for three different slopes:

- Optimal slope: 31° (calculated via PVGIS Tool for Pantelleria location);
- 10° (average value for pergolas and carports roof slope);
- Horizontal: 0° (*cannizzato* or external flooring slope).

The evaluated peak power of the photovoltaic systems, consisting of polycrystalline panels, is equal to $1kW_p$. Electricity production is calculated via PVGIS Tool for Pantelleria location (Latitude: 36.76; Longitude: 12.04), considering 14% of system loss. Figure 33 shows annual average electricity production from a $1kW_p$ south oriented photovoltaic system according to three different slopes.

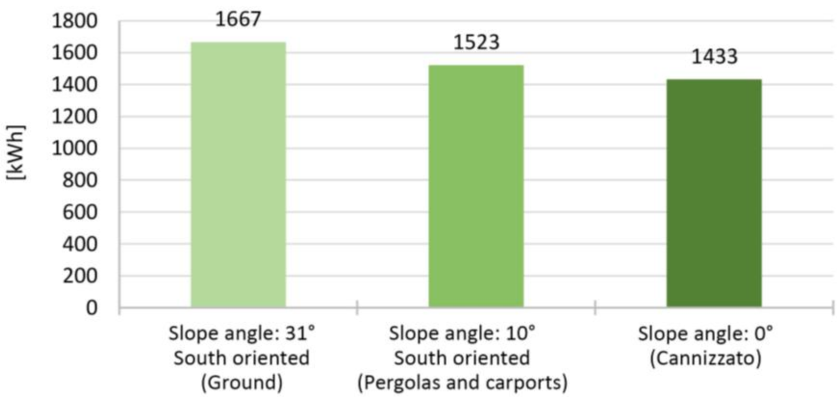


Figure 33. Annual average electricity production from a $1kW_p$ photovoltaic system

Figure 34 shows average monthly electricity production from a $1kW_p$ south oriented photovoltaic system according to three different slopes.

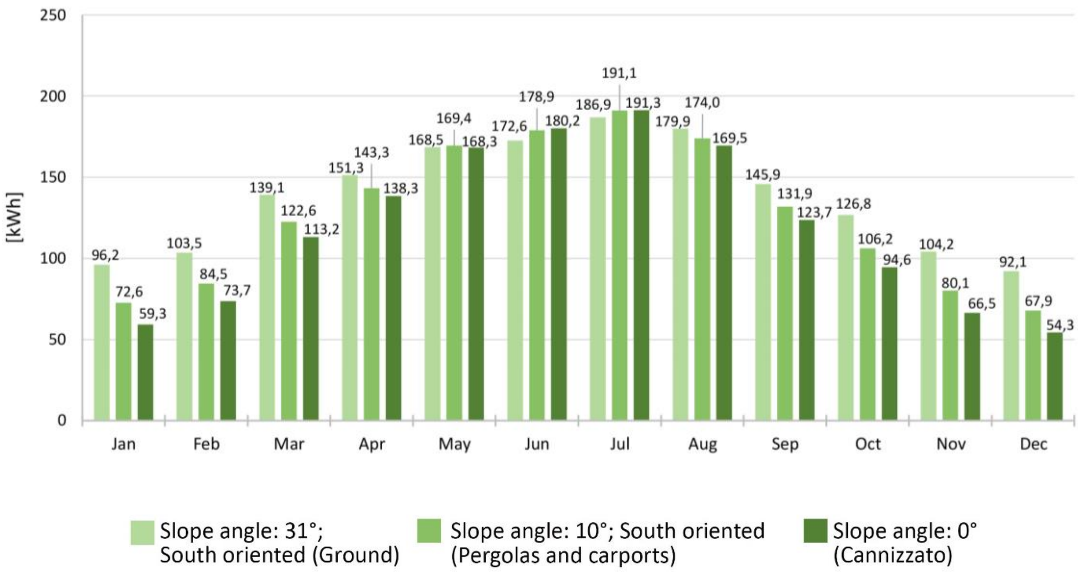


Figure 34. Average monthly electricity production from 1 kW_p photovoltaic system

Referring to Figure 34, it is noticeable that the optimal slope allows to have a higher energy production in winter months, which are characterized by a lower incident solar radiation. Also, the other two slope configurations, which better integrate photovoltaic systems on existing or specifically designed structures, however, guarantee a high energy production.

The following photovoltaic system technologies are assessed:
- Polycrystalline panels;
- Transparent BIPV panels;
- External photovoltaic flooring.

Main photovoltaic system technologies features are derived from product data sheets and are summarized in Table 65. Table 66 lists characteristics required according to different photovoltaic technologies in order to install a 1kW$_p$ photovoltaic system.

Table 65. PV system technology features

PHOTOVOLTAIC SYSTEM TECHNOLOGY	Nominal peak power	Nominal area	Efficiency
	[W$_p$]	[m^2]	[%]
Polycrystalline panels	300	1.69	17.8
Transparent BIPV panels	240	1.63	14.9
External photovoltaic flooring	100	0.72	13.9

Table 66. 1kW$_p$ photovoltaic system characteristics

PHOTOVOLTAIC SYSTEM TECHNOLOGY	Number of panels/tiles	PV system area
		[m^2]
Polycrystalline panels	4	6.7
Transparent BIPV panels	5	8.2
External photovoltaic flooring	10	7.2

Solar thermal system

Solar thermal system energy production is calculated for a 2.5 m^2 south oriented panel with optimal slope (31°). The calculations are performed according to UNI EN 12975-2:2005 and UNI/TS 11300-4:2016 as shown in Eq. (2) and Eq. (3):

$$\eta_c = \eta_0 - a_1 \cdot \theta^*_m - a_2 \cdot I \cdot (\theta^*_m)^2 \quad (2)$$

where: η_0 is instant efficiency
η_c is panel efficiency
a_1 and a_2 are panel parameters
I is irradiance

θ^*_m is defined as $\theta^*_m = (\theta_{mf} - \theta_{ae}) / I$

where: θ_{mf} is water average temperature

θ_{ae} is external temperature

$$E = \eta_c \cdot H \quad (3)$$

where: E is produced energy

η_c is instant efficiency

H is global radiation

Figure 35 shows average monthly energy production from solar system. Average monthly global radiation values are calculated via PVGIS Tool for Pantelleria location. Monthly energy external temperature is derived from Italian Standard for conventional climatic data UNI 10349-1:2016. Solar thermal panel parameters used for calculating are derived from product data sheets.

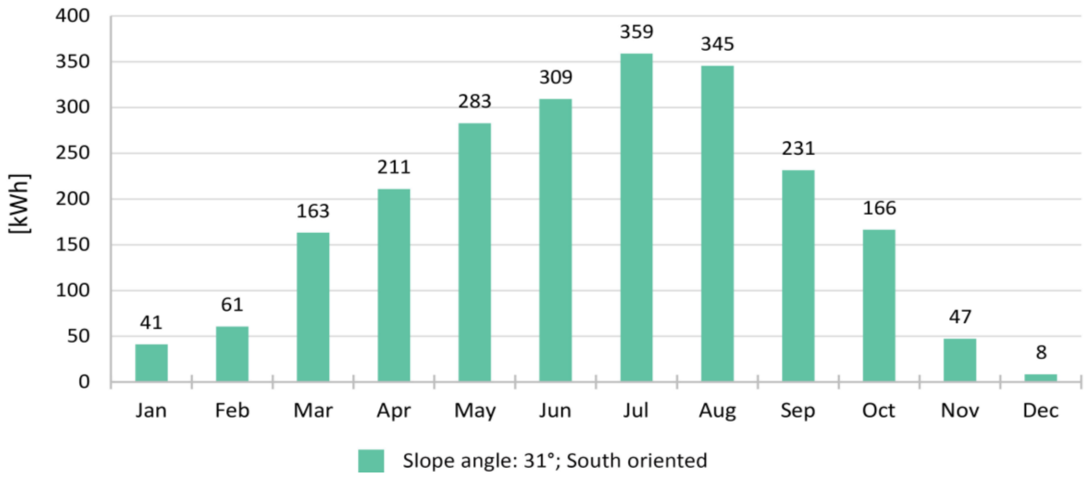


Figure 35. Average monthly energy production from solar system

Therefore, if on-site solar energy exploitation is recommended, the use of wind energy, which is a potential renewable energy source according to "*Agenda per la Transizione Energetica dell'Isola di Pantelleria"* (2020), it is not proposed within energy efficiency measures since the introduction of wind power system requires a timely study with respect to the installation site of the micro-eolic plants. Pantelleria Island is a high wind site, but the wind is often disturbed by the conformation of the land. Furthermore, according to DP 10/2017, it is currently prohibited the installation of wind power systems throughout the island territory.

5.3.2 Definition of energy retrofit scenarios

By combining alternative energy efficiency measures (EEMs), different energy retrofit scenarios are provided. The proposed interventions are distinguished into:

- Systems intervention: energy efficiency measures concern only building systems. In this case, proposed systems solutions are "not invasive", which means that their installation requires limited non-destructive interventions on building envelope components (walls and slab) and does not interfere significantly with building operation;
- Energy intervention: energy efficiency measures concern both building envelope and building systems. In this case, proposed systems solutions are "invasive", which means that their installation requires destructive interventions on building envelope components, including walls and slab breaking for distribution subsystem and terminal devices installation, making building temporarily unusable.

Retrofit scenarios are defined based on the following assumptions:

1. Buildings with continuous occupancy:
    a. In case of a slight renovation, where envelope is not involved (CS) and where envelope is partially involved (BE1), multi split heat pumps for space heating and space cooling are proposed as "not invasive" building system solutions with eventual replacement of existing system for DHW production (BS3, BS4). Photovoltaic system with battery electricity storage is introduced (RS1);
    b. In case of major renovation, where plasters are refurbished, windows and doors are replaced and inferior slab has to be reconstructed, air-to water heat pump is proposed as combined system for space heating, space cooling and DHW production. Radiant floor panels are proposed as terminal devices (BS5) and photovoltaic system with battery electricity storage is introduced (RS1);
    c. In case of complete major renovation, where envelope is totally involved (BE6), space cooling is no longer needed. Air-to-water heat pump (BS1) or biomass boiler (BS2) are proposed as "invasive" building systems solutions for space heating and DHW production and low temperature radiators are proposed as terminal devices. Photovoltaic system with battery electricity storage (RS1) and solar thermal systems (RS3) are coupled respectively with BS1 and BS2 building systems EEMs.

2. Buildings with occasional occupancy:
    a. For any situation, replacement of existing system for DHW production is proposed (BS6). In this case, renewable energy sources are not introduced: the investment cost for photovoltaic and solar thermal systems, indeed, appears high considering the actual renewable energy use, which is limited to summer months -from May to September- in which the building is effectively occupied;
    b. In cases in which space cooling is needed or required, multi-split heat pumps are proposed as building systems with eventual replacement of existing system for DHW production (BS7, BS8). Since cooling system is assumed as not present at the current state, its introduction implies higher final consumption than the current ones; to overcome this, photovoltaic system, has to be introduced. Photovoltaic system is proposed without battery electricity storage, since its introduction is expensive if compared to its actual exploitation, which is limited to summer months from May to September.

Retrofit scenario performances are evaluated for each *dammuso* archetype model. Table 67 shows the overall matrix reporting retrofit scenarios derived from the combination of the different identified energy efficiency measures for building envelope, building systems and renewable energy sources. Retrofit scenarios from S1 to S6 are referred to buildings with continuous occupancy (permanent houses), while retrofit scenarios from S7 to S9 are related to buildings with occasional occupancy (summer holiday houses).

Table 67. Retrofit scenarios overall matrix

			EEMs													
			ENVELOPE			**SYSTEMS**								**RENEWABLE ENERGY SOURCES**		
			CURRENT STATE	BE1	BE6	BS1	BS2	BS3	BS4	BS5	BS6	BS7	BS8	RS1	RS2	RS3
BUILDINGS WITH CONTINUOUS OCCUPANCY	**SCENARIOS**	S1	●					●						●		
		S2	●						●					●		
		S3		●					●					●		
		S4		●						●				●		
		S5			●	●								●		
		S6			●		●									●
BUILDINGS WITH OCCASIONAL OCCUPANCY		S7	●								●				●	
		S8	●									●			●	
		S9	●										●		●	

5.3.3 Modelling of energy retrofit scenarios of *dammusi* archetypes

On the basis of alternative energy efficiency measures combined for the definition of nine retrofit scenarios for each *dammuso* building archetype, energy performance of the identified retrofit scenarios is assessed through the implementation of the energy model developed for each archetype set out in detail in Paragraph 5.1.2. Subsequent sections report in detail energy models implementation of the three *dammusi* archetypes.

INPUT DATA RELATED TO OCCUPANCY

The building category selected for buildings with continuous occupancy according to DPR 412/93 is E.1(1) (residential buildings, continuous occupation).
The building category selected for buildings with occasional occupancy according to DPR 412/93 is E.1(2) (holiday houses, occasional occupation). The calculations are performed by considering the standard occupancy defined by the UNI/TS 11300-1:2014 with the assumptions for both cases (see page 37).

CONVERSION FACTORS TO PRIMARY ENERGY AND CO_{2eq} EMISSION FACTORS

Primary energy consumption is calculated using both national and local conversion factors. Since retrofit scenarios introduce additional sources of energy in addition to electricity, different conversion factors to primary energy and to CO_{2eq} emissions are employed in the calculations. Table 68 introduces conversion factors for biomass and for energy produced by photovoltaic system, solar thermal system and heat pump. National conversion factors for biomass and energy produced from renewable energy sources are assumed even as local factors for Pantelleria Island. In addition, CO_{2eq} emission factors are listed in the last column of the table. National and local conversion factors assumed for electricity are those reported in Table 55 at page 60.

Table 68. Conversion factors to primary energy and CO_{2eq} emission factors

ENERGY CARRIER	PRIMARY ENERGY			CO_{2eq} EMISSIONS
	Primary energy conversion factor (f_p)	Non-renewable primary energy conversion factor ($f_{p,nren}$)	Renewable primary energy conversion factor ($f_{p,ren}$)	CO_{2eq} emission factor (ENEA)
	National conversion factors (D.M. 26.6.2015)	National conversion factors (D.M. 26.6.2015)	National conversion factors (D.M. 26.6.2015)	
BIOMASS	1.00	1.20	0.80	0.05
ENERGY PRODUCED BY PV SYSTEM, SOLAR THERMAL SYSTEM AND HEAT PUMPS	1.00	0.00	1.00	0.00

ARCHETYPE 1: ***DAMMUSO TRIPARTITO***

The energy model of the current state Archetype 1 is declined into three different current models in order to carefully consider different envelope features (external plaster presence or absence) and occupancy types (continuous or occasional):

- Current state model for buildings with stone façade and continuous occupancy is identified by code CS01;
- Current state model for buildings with plastered façade and continuous occupancy is identified by code CS001;
- Current state model for buildings with stone façade and occasional occupancy is identified by code CS01′.

Table 69 summarizes envelope components average thermal transmittance for current state and every energy efficiency measure compared to thermal transmittance limit value imposed for climatic zone B according to Appendix B, DM 26.06.2015 (since 2021).

Table 69. Envelope components average thermal transmittance

		Walls average thermal transmittance	**Doors average thermal transmittance**	**Windows average thermal transmittance**	**Roof average thermal transmittance**
		[W/m^{2}K]	[W/m^{2}K]	[W/m^{2}K]	[W/m^{2}K]
LIMIT VALUE		0.40	3.00	3.00	0.32
EEMs	CS01	0.72	2.45	4.9	1.52
	CS001	0.71	2.45	4.9	1.52
	CS01′	0.72	2.45	4.9	1.52
	BE1	0.29	1.93	2.3	0.30
	BE2	0.53	1.93	2.3	0.86
	BE3	0.28	1.93	2.3	1.52
	BE4	0.52	1.93	2.3	1.52
	BE5	0.41	1.93	2.3	0.86
	BE6	0.25	1.93	2.3	0.30

Energy needs for space heating and cooling are calculated in compliance with UNI EN ISO 52016-1:2018 and UNI/TS 11300-1:2014.

Annual specific energy needs for space heating for every envelope efficiency measure is shown in Figure 36. The energy needs of CS01′ is the same of CS01.

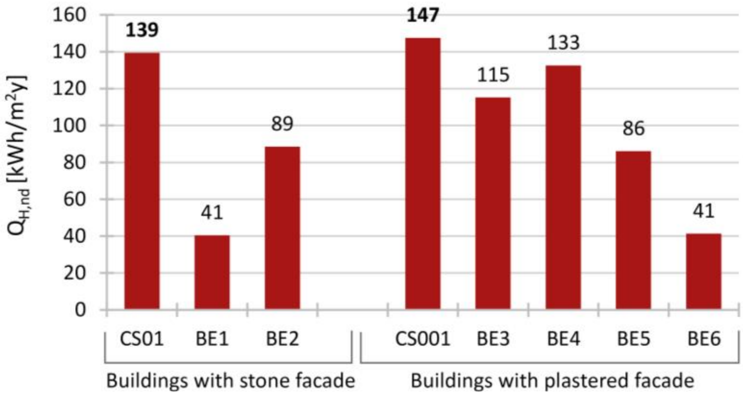


Figure 36. Annual energy needs for space heating for the different EEMs

Annual specific energy needs for space cooling for every envelope efficiency measure is shown in Figure 37. The energy needs of CS01′ is equal to the one of CS01.

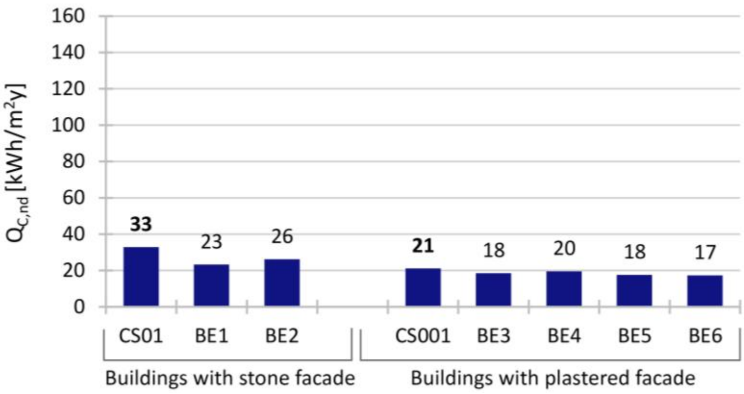


Figure 37. Annual energy needs for space cooling for the different EEMs

Analyzing obtained results and taking into account existing constraints (see page 35), the following envelope energy efficiency measures are excluded in the definition of energy retrofit scenarios for *dammusi* buildings:

- BE2: improvements in building energy needs are not as significant as those arising from measure BE1. Since no specific constraints are provided about internal plaster composition, measure BE1 is preferred;
- BE3: improvements in building energy needs are limited since the large internal surface of vault is not involved in the intervention, which only affects external surface of the walls. In addition, since the external façade plaster must be lime-based according to the "*Piano Territoriale Paesistico dell'Isola di Pantelleria*" (2000), the use of innovative plaster on external surface of the walls has to be excluded;
- BE4: improvements in building energy needs are limited since the large internal surface of vault is not involved in the intervention, which only affects external surface of the walls. However, when existing façade plaster is compromised, a traditional natural mineral lime-based plaster can be used on external surface of the walls;

- BE5: improvements in building energy needs are not as relevant as those arising from measure BE6. Since no specific constraints are provided about internal plaster composition, measure BE6, which also includes the use of a traditional natural mineral lime-based plaster on external surface of the walls, is preferred.

In conclusion, the following envelope efficiency measures are those selected and implemented in energy models to assess energy performance of retrofit scenarios:

- BE1
- BE6

Since current state energy need for buildings with stone façade (CS01) and buildings with plastered façade (CS001) are not substantially different, scenarios results are evaluated only for CS01 case.

The threshold value equal to 15 kWh/m^{2}y, which meets Passivehouse standard according to Recommendation 2016/1318/EU, is set for energy need for space cooling ($Q_{C,nd}$). Below this value, no systems for space cooling are introduced.

Energy need for domestic hot water (DHW) is calculated in compliance with UNI/TS 11300-2:2019. As regards buildings with continuous occupancy, DHW production is provided throughout the whole year. Annual energy need for DHW is equal to 454 kWh/y, considering an estimated DHW consumption equal to 50 l/d (18 m^3/y). As regards buildings with occasional occupancy, DHW production is provided in summer months, from May to September. Annual energy need for DHW is equal to 190 kWh/y, considering an estimated DHW consumption equal to 50 l/d for five months (7.5 m^3/y). Figure 38 shows annual specific energy needs for DHW for buildings with continuous and occasional occupancy.

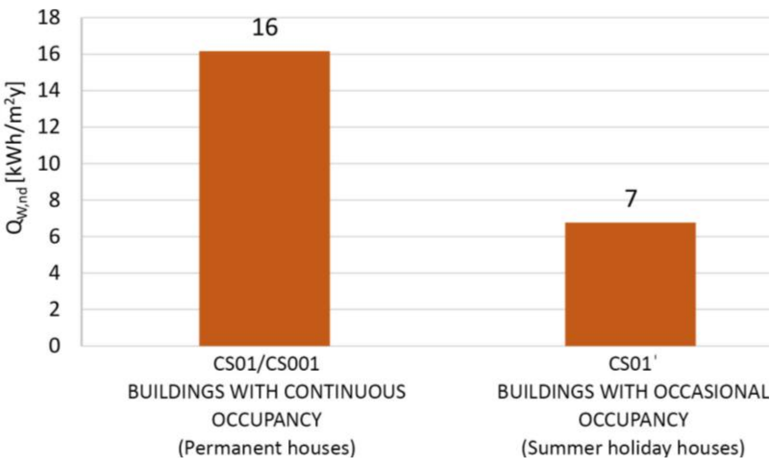


Figure 38. Annual energy needs for DHW according to occupancy type

Heating, cooling and DHW production systems seasonal generation efficiencies referred to non-renewable primary energy, calculated according to UNI/TS 1300-2:2019, are reported in Table 70 for every energy efficiency measure.

Table 70. Systems generation efficiency referred to non-renewable primary energy

		Heating system generation efficiency	Cooling system generation efficiency	DHW production system generation efficiency
		[%]	[%]	[%]
EEMs	CS01/CS01’	51.3	-	38.5
	BS1	277.5	-	190.4
	BS2	203.9	-	227.8
	BS3	268.1	118.9	38.5
	BS4	269.5	118.9	193.5
	BS5	368	248.2	190.4
	BS6	-	-	197.7
	BS7	-	118.9	38.5
	BS8	-	118.9	197.7

Scenario results are obtained introducing a $1kW_p$ south oriented PV system with optimal slope (31°). However, $1kW_p$ PV system production and monthly electricity coverage is assessed also for other different slopes (10° for pergolas; horizontal for *cannizzato* or external flooring). Therefore, on the basis of these results and taking into account PV system technology features, it is possible to calculate the peak power that can be installed according to the available area for PV system installation (on ground, on pergolas or on *cannizzato*). For example, available *cannizzato* area for *dammuso* Archetype 1 is equal to 20.0 m^2. Considering PV panels dimensions, the *cannizzato* allows the installation of 6 polycrystalline panels for a total installed peak power equal to 1.8 kW_p and a total installed area of 10.1 m^2.

ARCHETYPE 2: *DAMMUSO PER AGGREGAZIONE COMPLESSA*

The energy model of the current state Archetype 2 is declined into three different current models in order to carefully consider different envelope features (external plaster presence or absence) and occupancy types (continuous or occasional):

- Current state model for buildings with stone façade and continuous occupancy is identified by code CS02;
- Current state model for buildings with plastered façade and continuous occupancy is identified by code CS002;
- Current state model for buildings with stone façade and occasional occupancy is identified by code CS02’.

Table 71 summarizes envelope components average thermal transmittance for current state and every energy efficiency measure compared to thermal transmittance limit value imposed for climatic zone B according to Appendix B, DM 26.06.2015 (since 2021).

Table 71. Envelope components average thermal transmittance

		Walls average thermal transmittance	**Doors average thermal transmittance**	**Windows average thermal transmittance**	**Roof average thermal transmittance**
		[W/m^{2}K]	[W/m^{2}K]	[W/m^{2}K]	[W/m^{2}K]
LIMIT VALUE		0.40	3.00	3.00	0.32
EEMs	CS02	0.76	2.45	4.9	1.52
	CS002	0.75	2.45	4.9	1.52
	CS02’	0.76	2.45	4.9	1.52
	BE1	0.28	1.93	2.3	0.30
	BE2	0.54	1.93	2.3	0.86
	BE3	0.31	1.93	2.3	1.52
	BE4	0.54	1.93	2.3	1.52
	BE5	0.42	1.93	2.3	0.86
	BE6	0.25	1.93	2.3	0.30

Energy needs for space heating and cooling are calculated in compliance with UNI EN ISO 52016-1:2018 and UNI/TS 11300-1:2014.

Annual specific energy needs for space heating for every envelope efficiency measure is shown in Figure 39. The energy needs of CS02’ is the same of CS02.

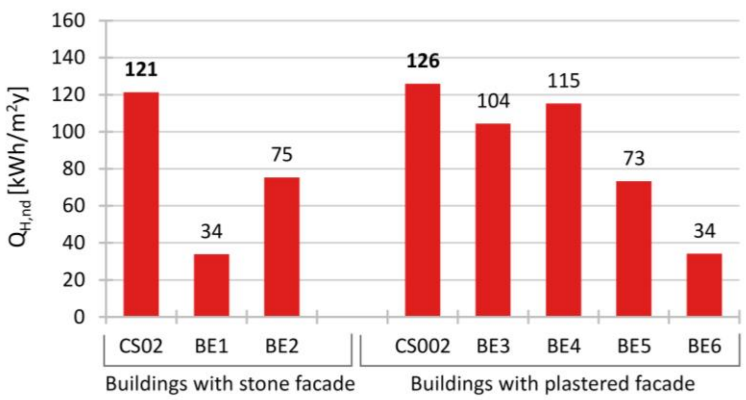


Figure 39. Annual energy needs for space heating for the different EEMs

Annual specific energy needs for space cooling for every envelope efficiency measure is shown in Figure 40. The energy needs of CS02’ is equal to the one of CS02

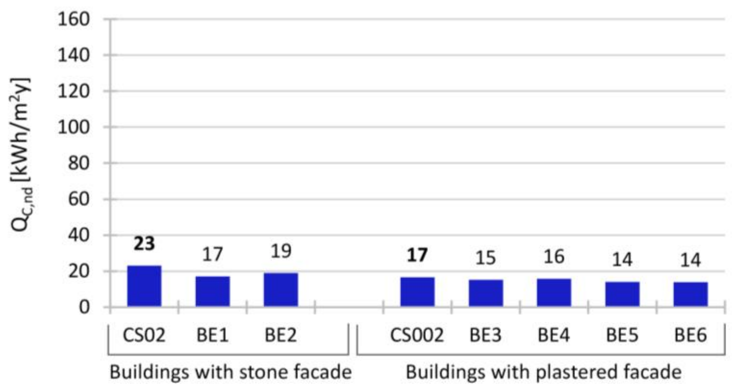


Figure 40. Annual energy needs for space cooling for the different EEMs

Analyzing obtained results and taking into account existing constraints (see page 35), the same assumptions made for envelope energy efficiency measures referred to Archetype 1 (see page 80) are considered. Therefore, the following envelope efficiency measures are those selected and implemented in energy models to assess energy performance of retrofit scenarios:

- BE1
- BE6

Since current state energy need for buildings with stone façade (CS01) and buildings with plastered façade (CS001) are not substantially different, scenarios results are evaluated only for CS01 case.

The threshold value equal to 15 kWh/m^{2}y, which meets Passivehouse standard according to Recommendation 2016/1318/EU, is set for energy need for space cooling ($Q_{C,nd}$). Below this value, no systems for space cooling are introduced.

Energy need for domestic hot water (DHW) is calculated in compliance with UNI/TS 11300-2:2019. As regards buildings with continuous occupancy, DHW production is provided throughout the whole year. Annual energy need for DHW is equal to 904 kWh/y, considering an estimated DHW consumption equal to 99 l/d (36 m^3/y). As regards buildings with occasional occupancy, DHW production is provided in summer months, from May to September. Annual energy need for DHW production is equal to 379 kWh/y, considering an estimated DHW consumption equal to 99 l/d for five months (15 m^3/y). Figure 41 shows annual specific energy needs for DHW for buildings with continuous and occasional occupancy.

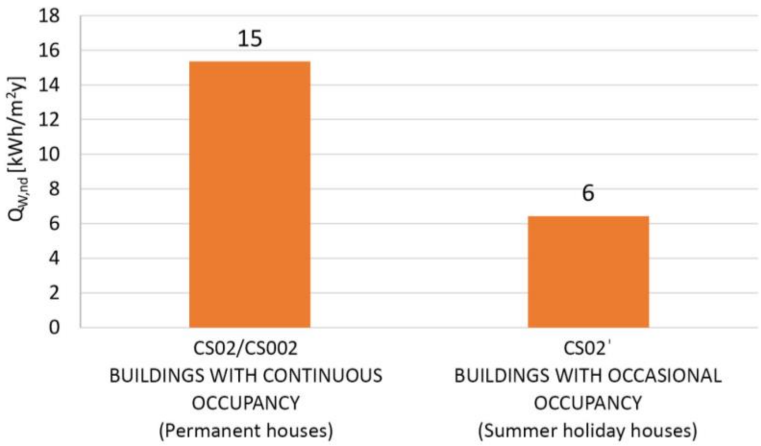


Figure 41. Annual energy need for DHW production according to occupancy type

Heating, cooling and DHW production systems seasonal generation efficiencies referred to non-renewable primary energy, calculated according to UNI/TS 1300-2:2019, are reported in Table 72 for every energy efficiency measure.

Table 72. Systems generation efficiency referred to non-renewable primary energy

		Heating system generation efficiency	Cooling system generation efficiency	DHW production system generation efficiency
		[%]	[%]	[%]
EEMs	CS02/CS02'	51.3	-	38.5
	BS1	273.7	-	191
	BS2	218.8	-	232.8
	BS3	238.9	131.6	38.5
	BS4	240.5	131.6	194.1
	BS5	363.5	304	191.0
	BS6	-	-	200.6
	BS7	-	131.6	38.5
	BS8	-	131.6	200.6

Scenario results are obtained introducing a 1kW$_p$ south oriented PV system with optimal slope (31°). However, 1kW$_p$ PV system production and monthly electricity coverage is assessed also for other different slopes (10° for pergolas; horizontal for *cannizzato* or external flooring). Therefore, on the basis of these results and taking into account PV system technology features, it is possible to calculate the peak power that can be installed according to the available area for PV system installation (on ground, on pergolas or on *cannizzato*). For example, available *cannizzato* area for *dammuso* Archetype 2 is equal to 26.9 m^2. Considering PV panels dimensions, the *cannizzato* allows the installation of 9 polycrystalline panels for a total installed peak power equal to 2.7 kW$_p$ and a total installed area of 15.2 m^2.

ARCHETYPE 3: *DAMMUSO PER AGGREGAZIONE COMPLESSA CON ELEMENTI ACCESSORI E PERTINENZE*

The energy model of the current state Archetype 3 is declined into three different current models in order to carefully consider different envelope features (external plaster presence or absence) and occupancy types (continuous or occasional):

- Current state model for buildings with stone façade and continuous occupancy is identified by code CS03;
- Current state model for buildings with plastered façade and continuous occupancy is identified by code CS003;
- Current state model for buildings with stone façade and occasional occupancy is identified by code CS03’.

Table 73 summarizes envelope components average thermal transmittance for every energy efficiency measure compared to thermal transmittance limit value imposed for climatic zone B according to Appendix B, DM 26.06.2015 (since 2021).

Table 73. Envelope components average thermal transmittance

		Walls average thermal transmittance	**Doors average thermal transmittance**	**Windows average thermal transmittance**	**Roof average thermal transmittance**
		[W/m^{2}K]	[W/m^{2}K]	[W/m^{2}K]	[W/m^{2}K]
LIMIT VALUE		0.40	3.00	3.00	0.32
EEMs	CS03	0.75	2.45	4.9	1.52
	CS003	0.68	2.45	4.9	1.52
	CS03’	0.75	2.45	4.9	1.52
	BE1	0.29	1.93	2.3	0.30
	BE2	0.53	1.93	2.3	0.86
	BE3	0.28	1.93	2.3	1.52
	BE4	0.53	1.93	2.3	1.52
	BE5	0.41	1.93	2.3	0.86
	BE6	0.25	1.93	2.3	0.30

Energy needs for space heating and cooling are calculated in compliance with UNI EN ISO 52016-1:2018 and UNI/TS 11300-1:2014.

Annual specific energy needs for space heating for every envelope efficiency measure is shown in Figure 42. The energy needs of CS03’ is the same of CS03.

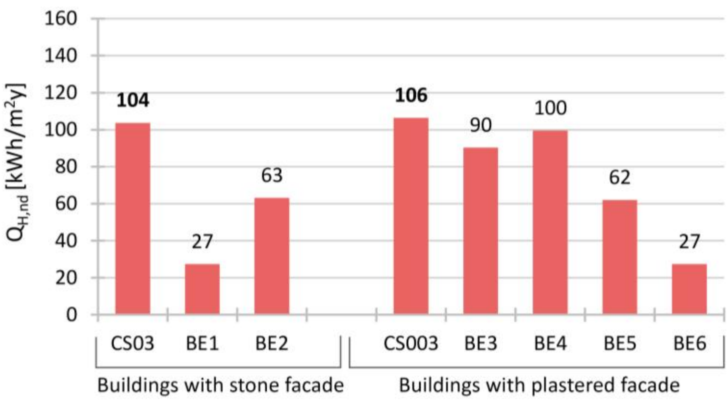


Figure 42. Annual energy needs for space heating for the different EEMs

Annual specific energy needs for space cooling for every envelope efficiency measure is shown in Figure 43. The energy needs of CS03' is equal to the one of CS03.

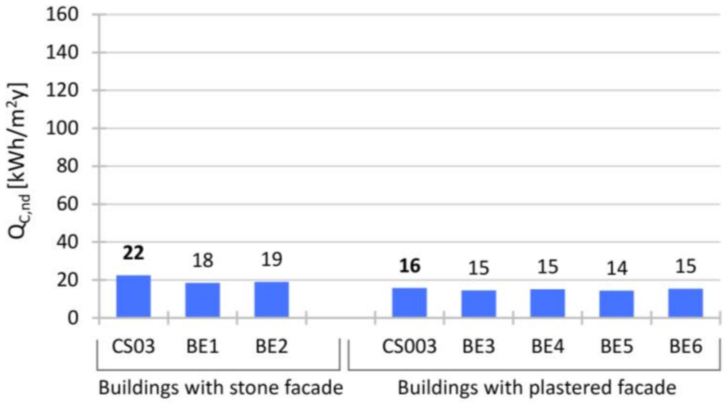


Figure 43. Annual energy needs for space cooling for the different EEMs

Analyzing obtained results and taking into account existing constraints (see page 35), the same assumptions made for envelope energy efficiency measures referred to Archetype 1 (see page 80) are considered. Therefore, the following envelope efficiency measures are those selected and implemented in energy models to assess energy performance of retrofit scenarios:

- BE1
- BE6

Since current state energy need for buildings with stone façade (CS03) and buildings with plastered façade (CS003) are not substantially different, scenarios results are evaluated only for CS03 case.

The threshold value equal to 15 kWh/m^{2}y, which meets Passivehouse standard according to Recommendation 2016/1318/EU, is set for energy need for space cooling ($Q_{C,nd}$). Below this value, no systems for space cooling are introduced.

Energy need for domestic hot water (DHW) is calculated in compliance with UNI/TS 11300-2:2019. As regards buildings with continuous occupancy, DHW production is provided throughout the whole year. Annual energy need for DHW is equal to 1480 kWh/y, considering an estimated DHW consumption equal to 162 l/d (59 m^3/y).

As regards buildings with occasional occupancy, DHW production is provided in summer months, from May to September. Annual energy need for DHW is equal to 620 kWh/y, considering an estimated DHW consumption equal to 162 l/d for five months (24 m^3/y). Figure 44 shows annual specific energy needs for DHW for buildings with continuous and occasional occupancy.

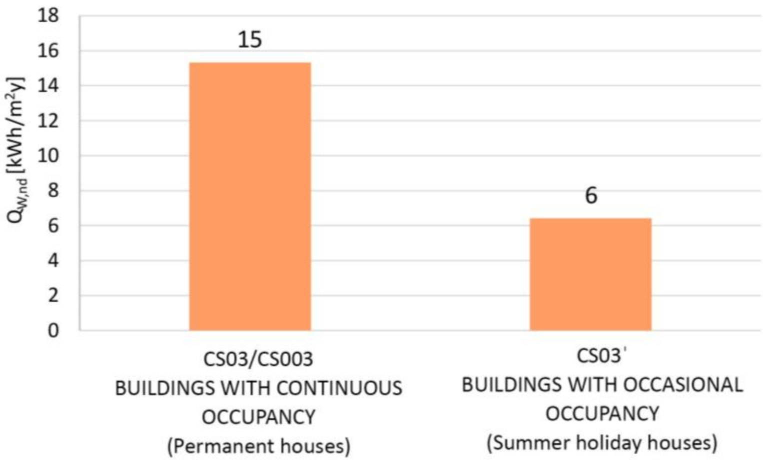


Figure 44. Annual energy needs for DHW according to occupancy type

Heating, cooling and DHW production systems seasonal generation efficiencies referred to non-renewable primary energy, calculated according to UNI/TS 1300-2:2019, are reported in Table 74 for every energy efficiency measure.

Table 74. Systems generation efficiency referred to non-renewable primary energy

		Heating system generation efficiency	Cooling system generation efficiency	DHW production system generation efficiency
		[%]	[%]	[%]
EEMs	CS03/CS03’	51.3	-	38.5
	BS1	270.2	-	191.6
	BS2	224.1	-	234.9
	BS3	222.3	166.6	38.5
	BS4	223.3	166.6	194.6
	BS5	359.3	373.8	191.7
	BS6	-	-	206.0
	BS7	-	166.6	38.5
	BS8	-	166.6	206.0

Scenario results are obtained introducing a 1kW$_p$ south oriented PV system with optimal slope (31°). However, 1kW$_p$ PV system production and monthly electricity coverage is assessed also for other different slopes (10° for pergolas; horizontal for *cannizzato* or external flooring). Therefore, on the basis of these results and taking into account PV system technology features, it is possible to calculate the peak power that can be installed according to the available area for PV system installation (on ground, on pergolas or on *cannizzato*). For example, available *cannizzato* area for *dammuso* Archetype 3 is equal to 44.1 m^2. Considering PV panels dimensions, the *cannizzato* allows the installation of 14 polycrystalline panels for a total installed peak power equal to 4.2 kW$_p$ and a total installed area of 23.6 m^2.

5.4 Retrofit scenarios assessment of *dammusi* archetypes

Retrofit scenarios energy performance results for the three archetypes are compared with current state results through a set of bar charts related to building energy needs, final energy uses and emissions. Furthermore, estimated energy savings as percentage are shown through four bar charts related to electricity, primary energy and CO_{2eq} emissions.

BUILDING ENERGY NEEDS

ENERGY NEED FOR SPACE HEATING AND SPACE COOLING

Annual energy needs for space heating and space cooling for retrofit scenarios and current state models are shown in Figures 45, 46, 47, respectively for Archetype 1, Archetype 2 and Archetype 3.

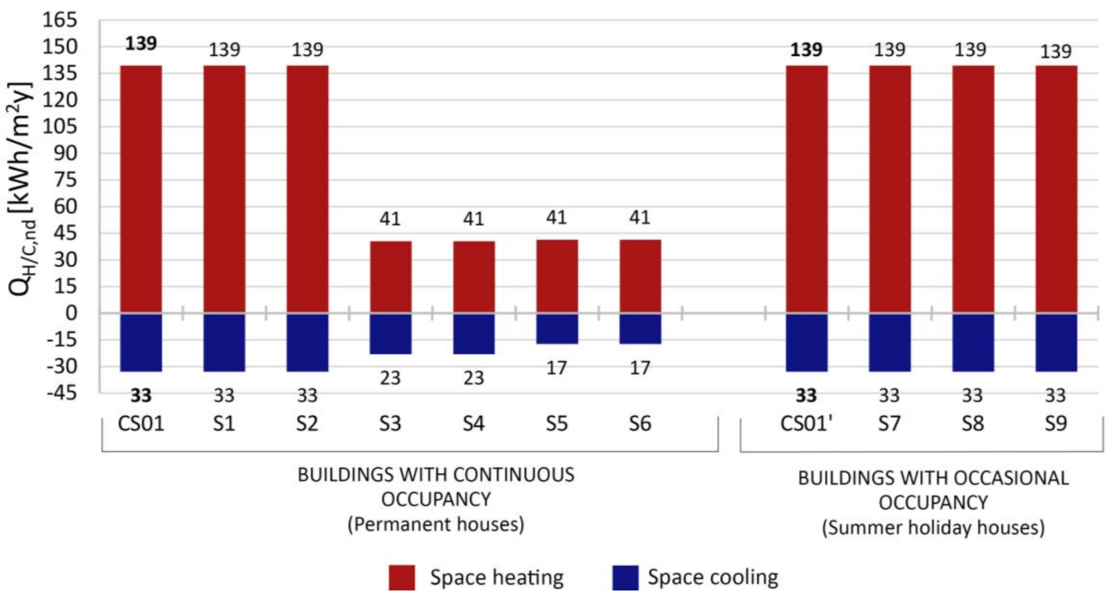


Figure 45. Annual energy needs for space heating and space cooling for Archetype 1

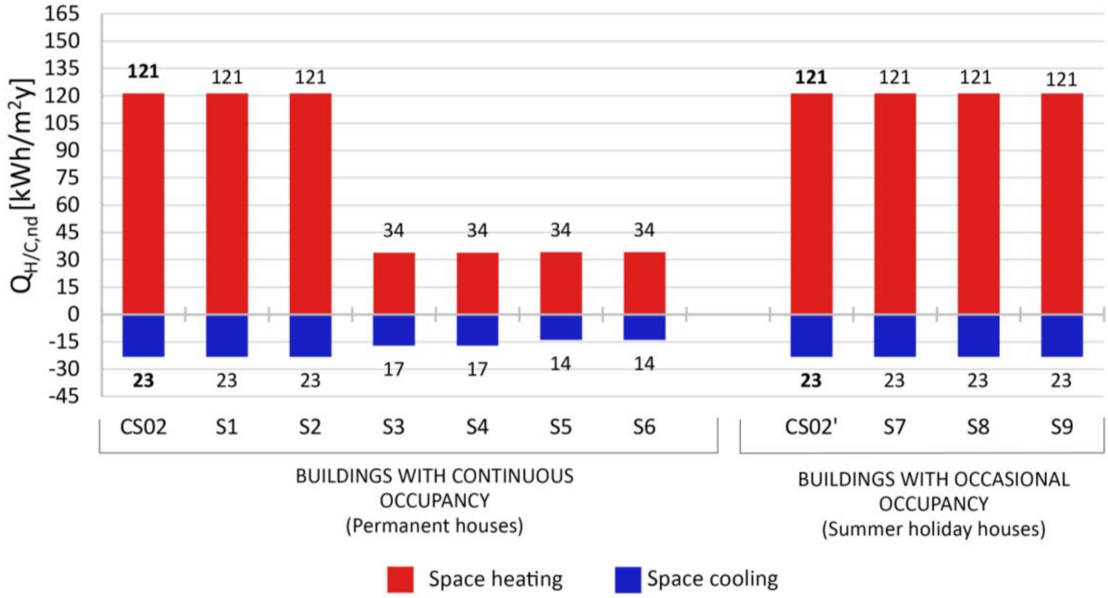


Figure 46. Annual energy need for space heating and space cooling for Archetype 2

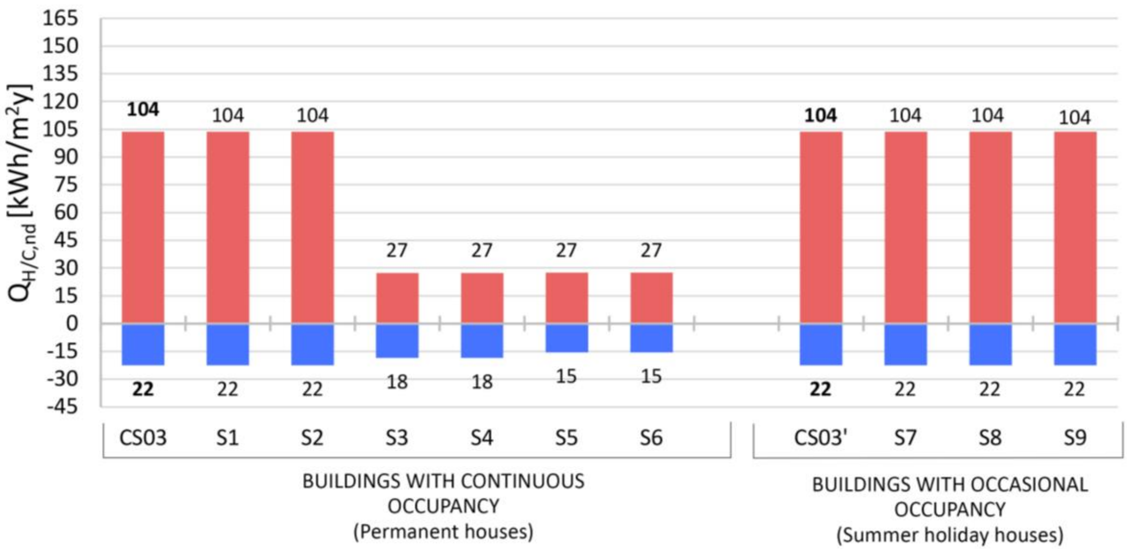


Figure 47. Annual energy needs for space heating and space cooling for Archetype 3

ENERGY NEED FOR DOMESTIC HOT WATER

Annual energy needs for DHW for retrofit scenarios and current state models are shown in Figures 48, 49, 50, respectively for Archetype 1, Archetype 2 and Archetype 3.

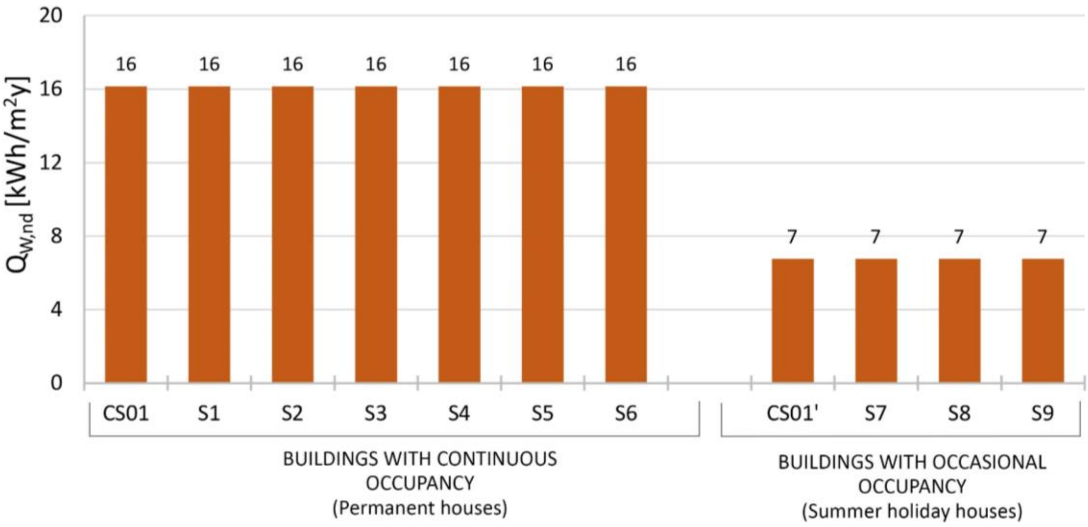


Figure 48. Annual energy needs for DHW for Archetype 1

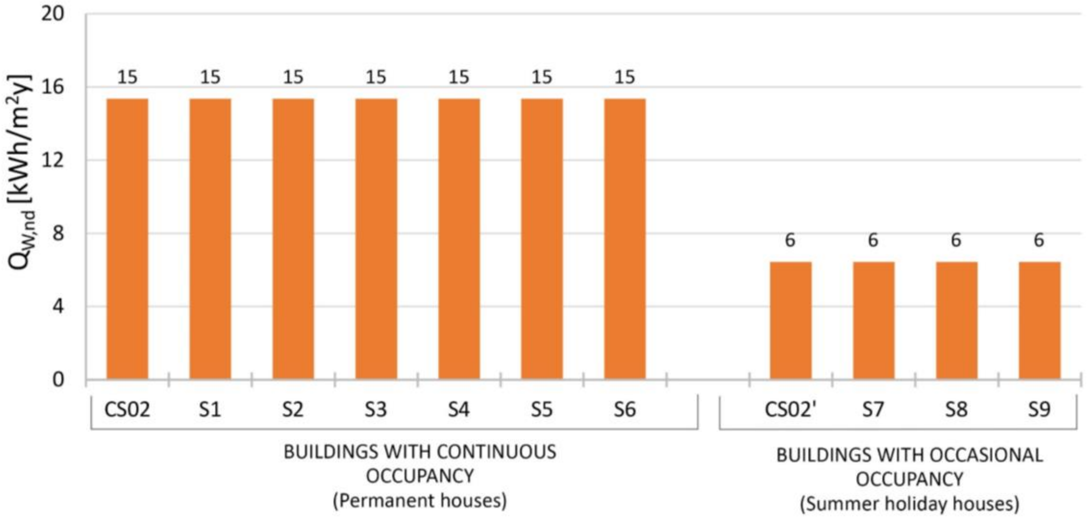


Figure 49. Annual energy needs for DHW for Archetype 2

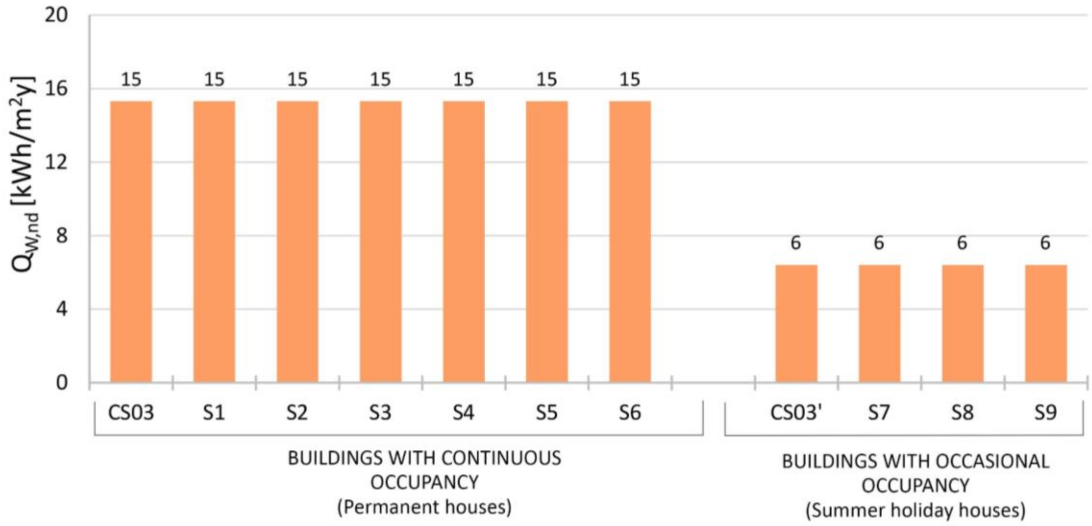


Figure 50. Annual energy need for DHW for Archetype 3

CONSUMPTIONS AND EMISSIONS

ON-SITE RENEWABLE ENERGY PRODUCTION

Figures 51, 52, 53 show coverage of annual electricity need from 1 kW_p photovoltaic system for retrofit scenarios and current state models taking into consideration three different possible installed photovoltaic system with different slopes, respectively for Archetype 1, Archetype 2 and Archetype 3. Electricity coverage is assessed monthly on the basis of average monthly electricity production from PV system. The percentage referred to 1 kW_p photovoltaic system, south oriented and with optimal slope, are assumed to obtain final energy uses and emission results for retrofit scenarios. Electricity needs are considered for space heating, space cooling and domestic hot water production. Electricity needs for lighting and equipment are not considered.

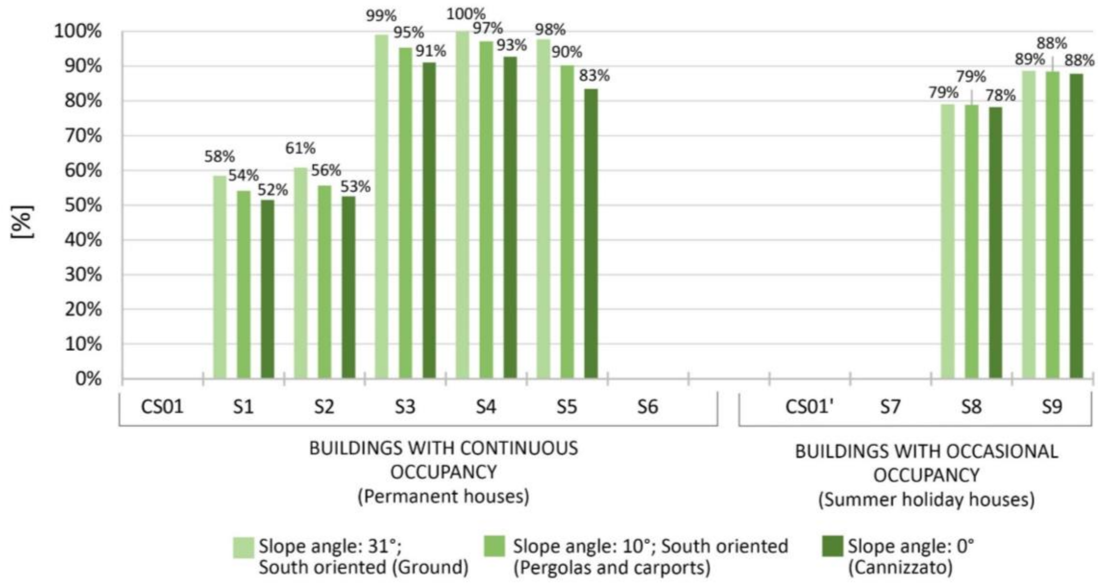


Figure 51. Coverage of annual electricity consumption from 1kW_p PV system for Archetype 1

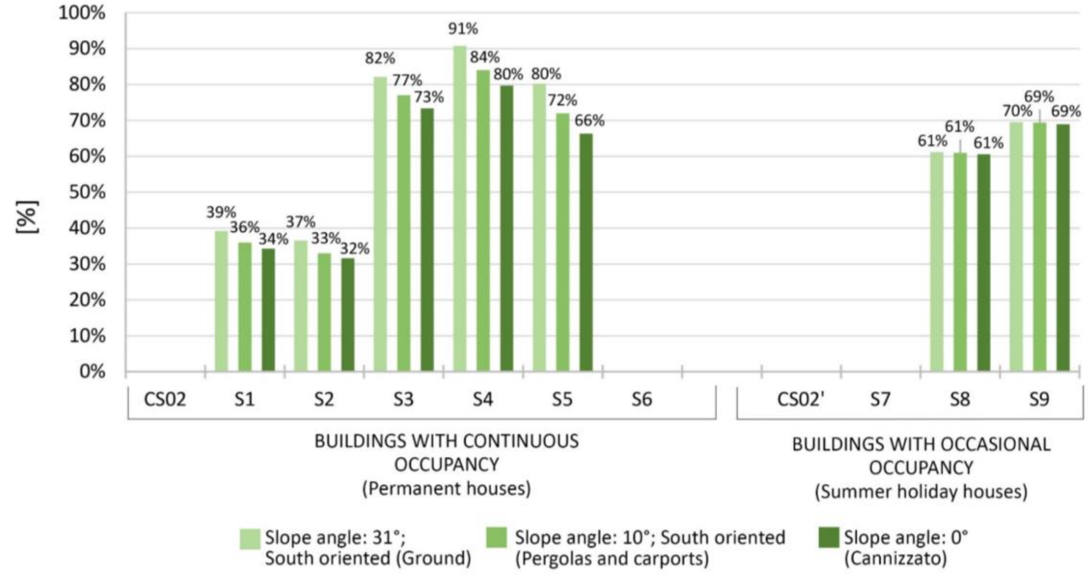


Figure 52. Coverage of annual electricity consumption from 1kW_p PV system for Archetype 2

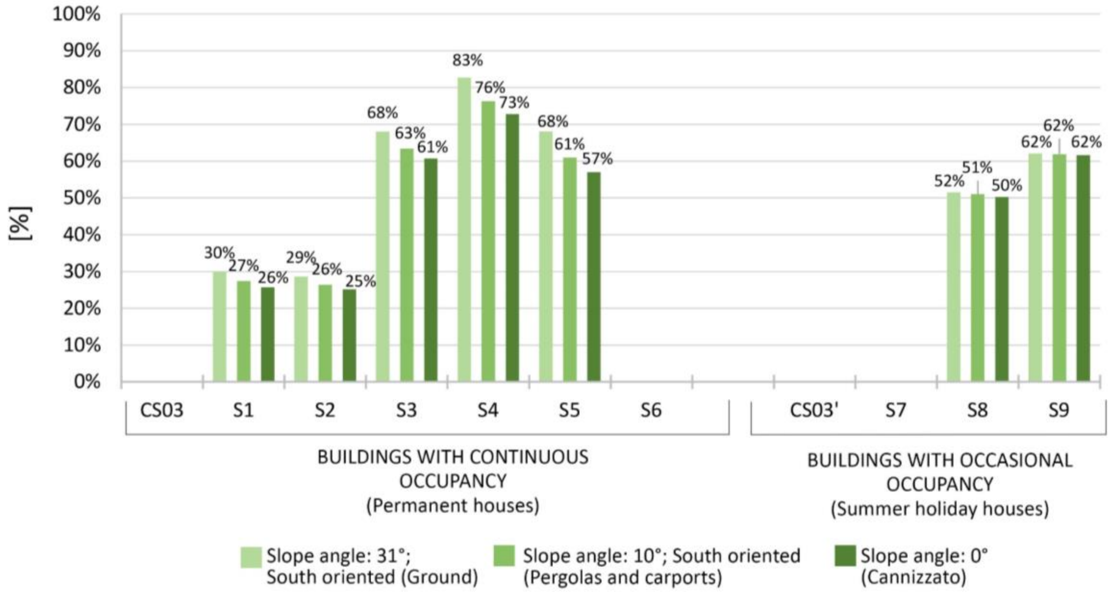


Figure 53. Coverage of annual electricity consumption from $1kW_p$ PV system for Archetype 3

Solar thermal system is implemented only in Scenary S6 for all archetypes. Coverage of annual domestic hot water production need from 2.5 m^2 solar thermal system is equal to 76%, 74% and 69%, respectively for Archetype 1, Archetype 2 and Archetype 3.

ELECTRICITY CONSUMPTIONS

Annual electricity consumptions subdivided into electricty taken from grid and produced by photovoltaic system for retrofit scenarios and current state models are shown in Figures 54, 55, 56, respectively for Archetype 1, Archetype 2 and Archetype 3.

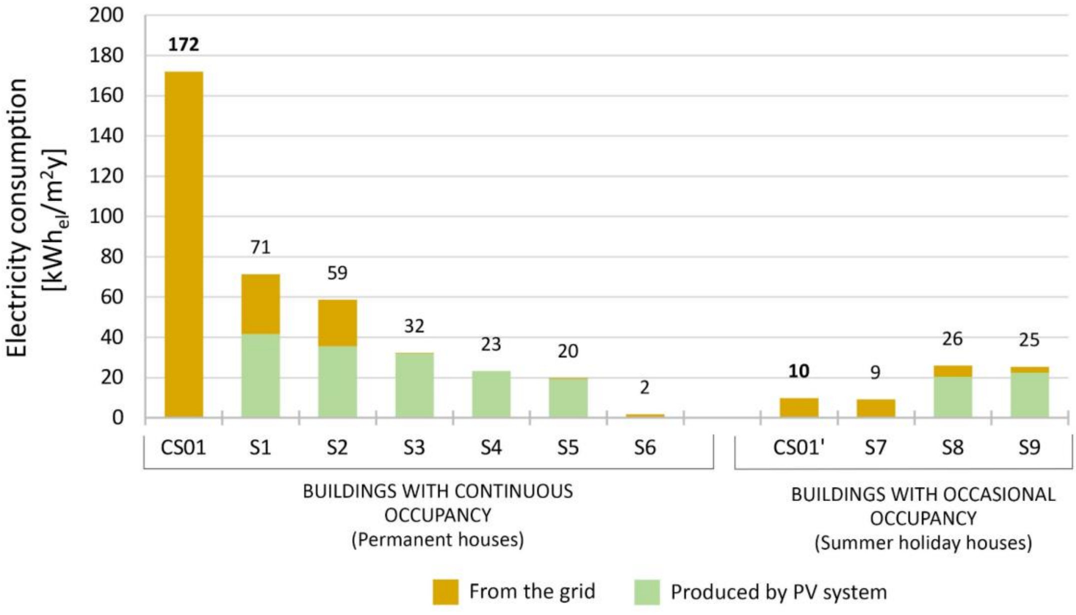


Figure 54. Annual electricity consumptions for Archetype 1

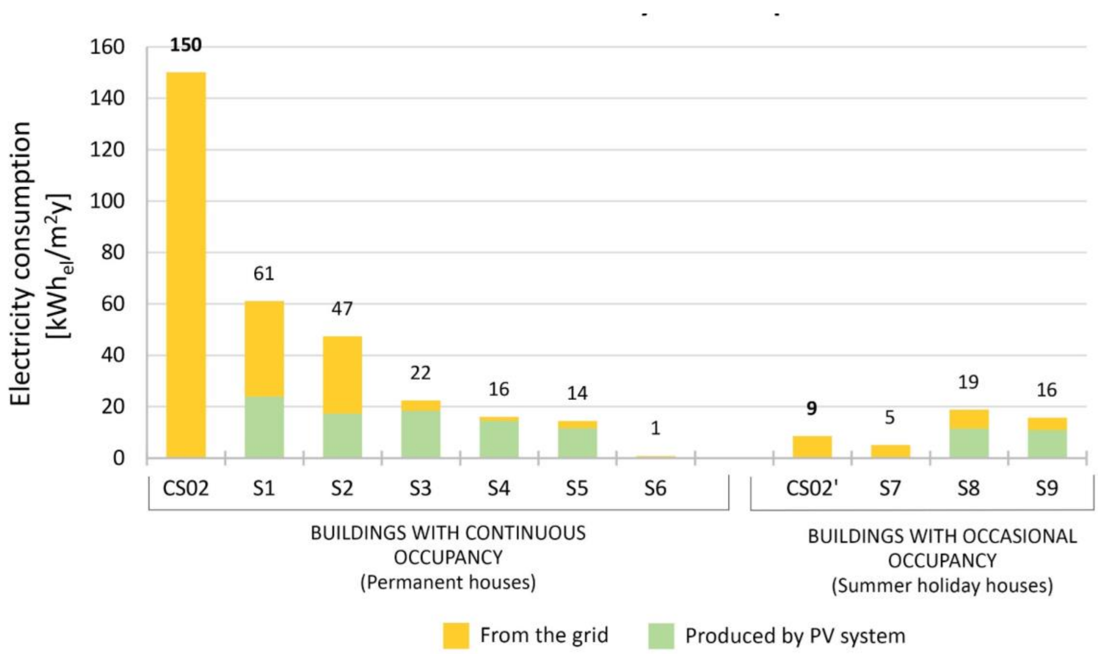


Figure 55. Annual electricity consumptions for Archetype 2

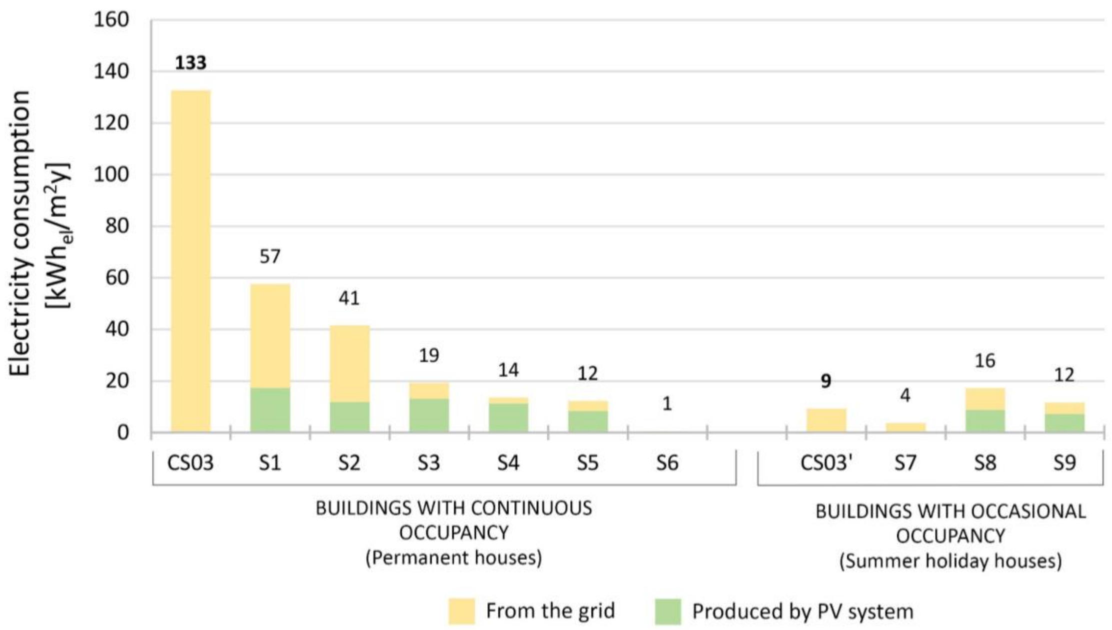


Figure 56. Annual electricity consumptions for Archetype 3

Scenario S6 involves the introduction of a biomass boiler for alla archetypes and its annual specific biomass consumption is equal to 23 kg/m^{2}y, 20 kg/m^{2}y, 17 kg/m^{2}y, respectively for Archetype 1, Archetype 2 and Archetype 3.

PRIMARY ENERGY CONSUMPTIONS AND EMISSIONS

Figures 57, 59, 61 show annual primary energy consumption calculated with both national and local conversion factors subdivided into renewable primary energy and non-renewable primary energy for retrofit scenarios and current state models, respectively for Archetype 1, Archetype 2 and Archetype 3.

Figures 58, 60, 62 show total annual primary energy consumption calculated with both national and local conversion for retrofit scenarios and current state models, respectively for Archetype 1, Archetype 2 and Archetype 3.

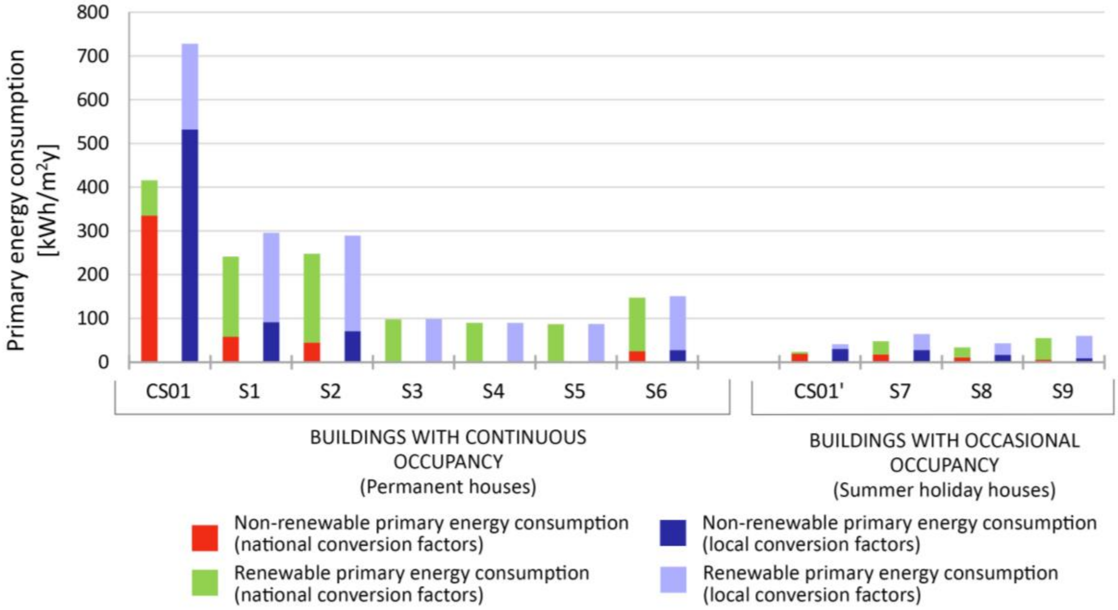


Figure 57. Annual primary energy consumption subdivided into renewable and non-renewable energy consumption for Archetype 1

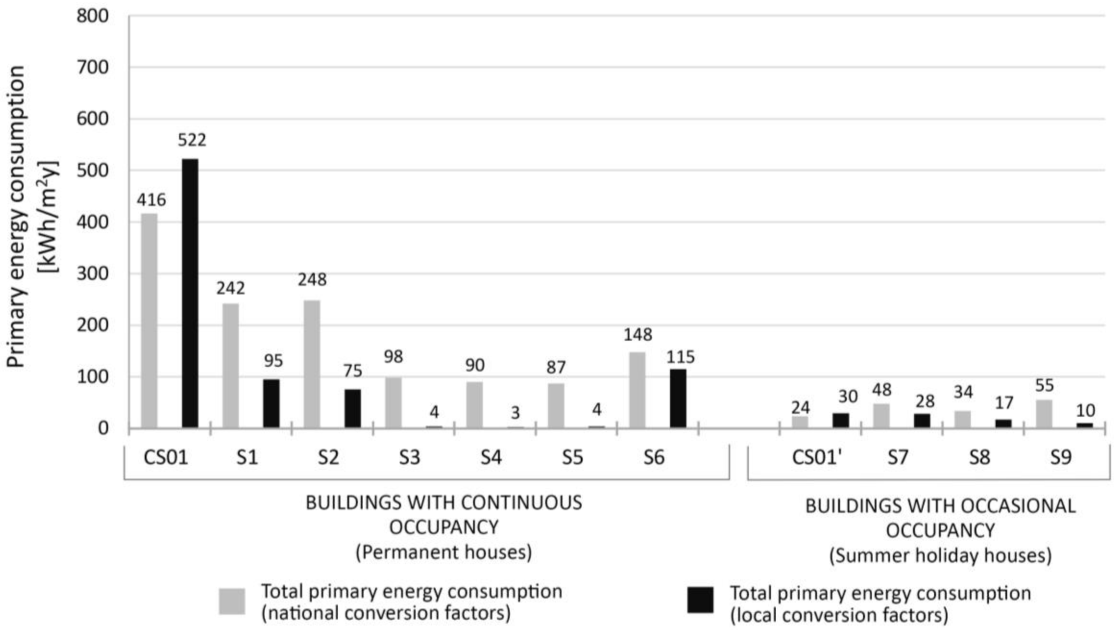


Figure 58. Total annual primary energy consumption for Archetype 1

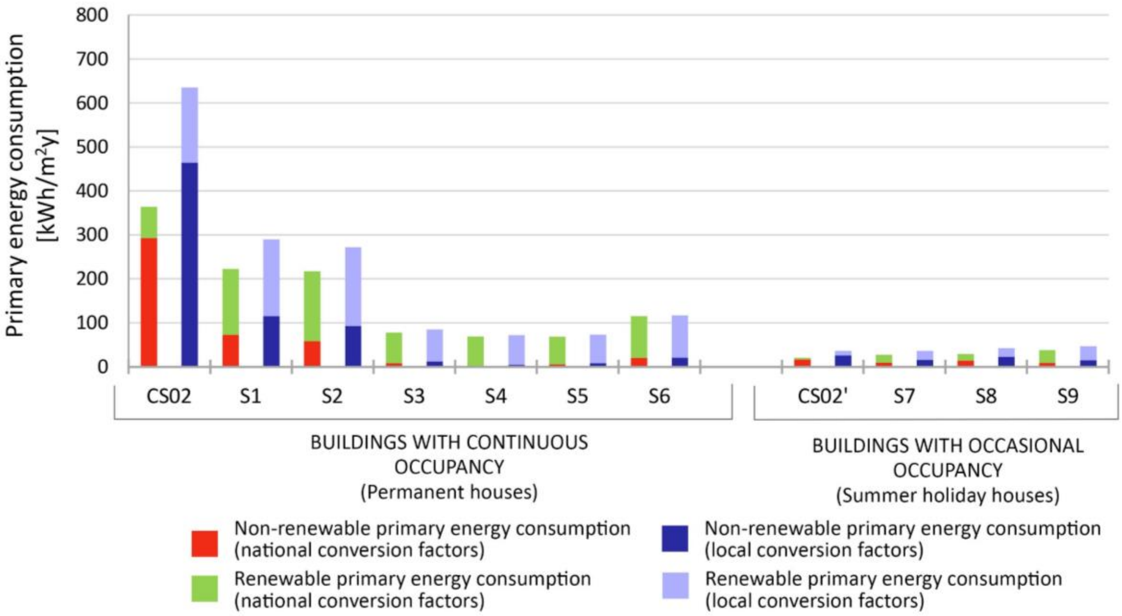


Figure 59. Annual primary energy consumption subdivided into renewable and non-renewable energy consumption for Archetype 2

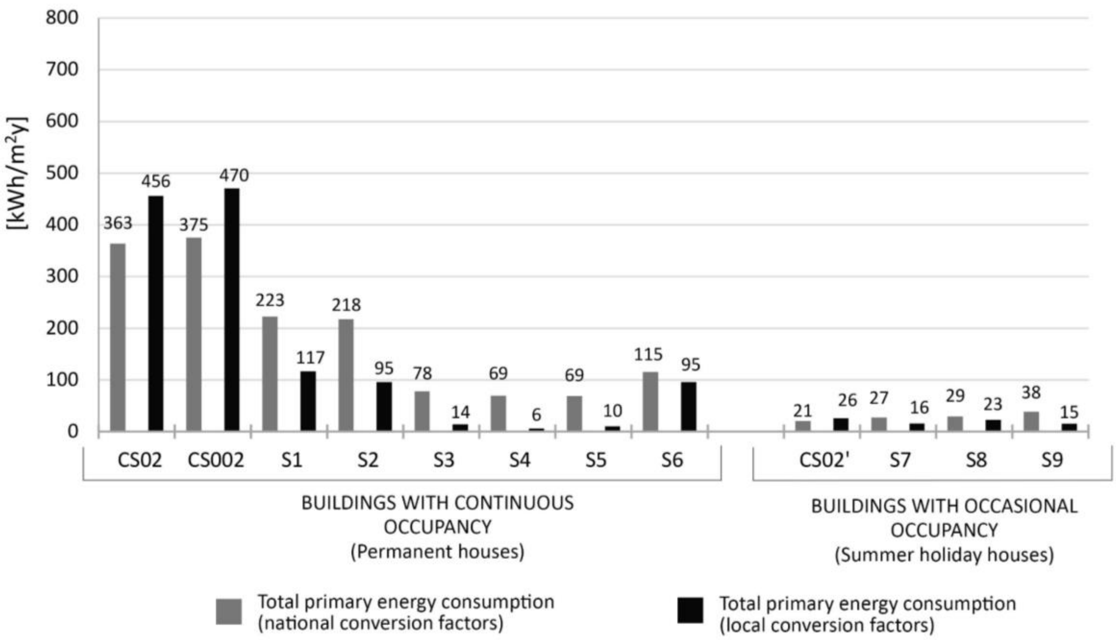


Figure 60. Total annual primary energy consumption for Archetype 2

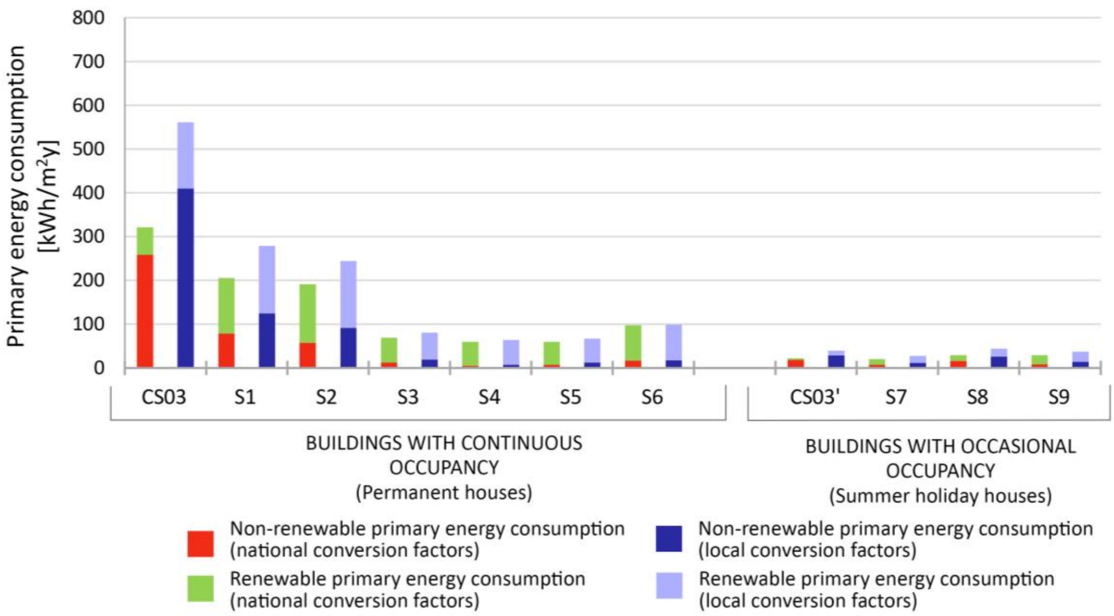


Figure 61. Annual primary energy consumption subdivided into renewable and non-renewable energy consumption for Archetype 3

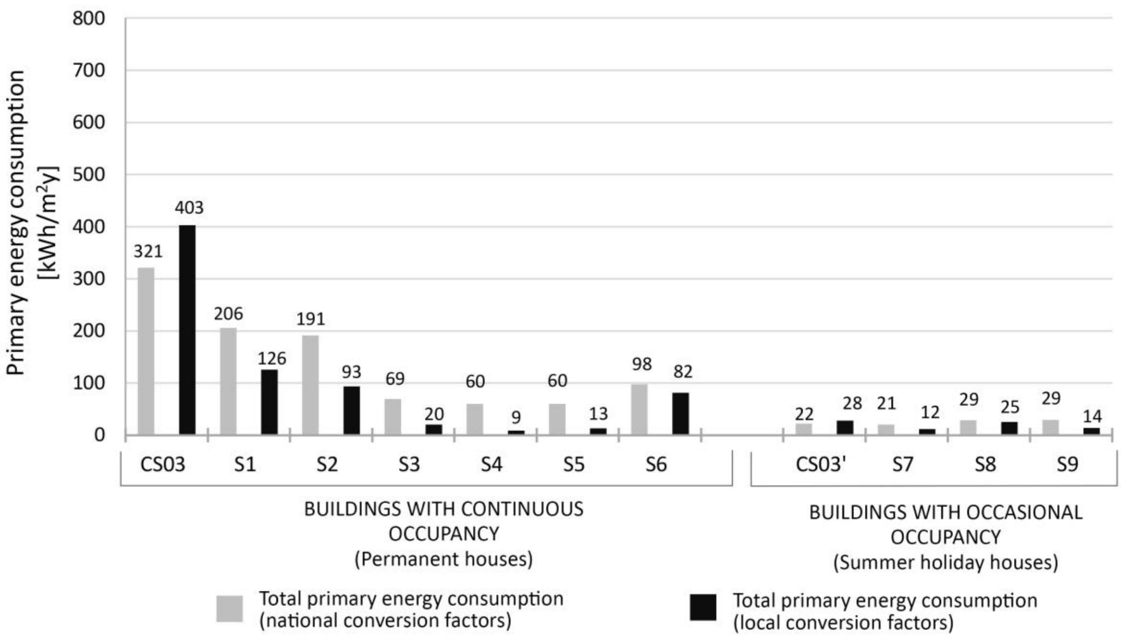


Figure 62. Total annual primary energy consumption for Archetype 3

Figures 63, 64, 65 show annual CO_{2eq} emissions calculated for retrofit scenarios and current state models, respectively for Archetype 1, Archetype 2 and Archetype 3.

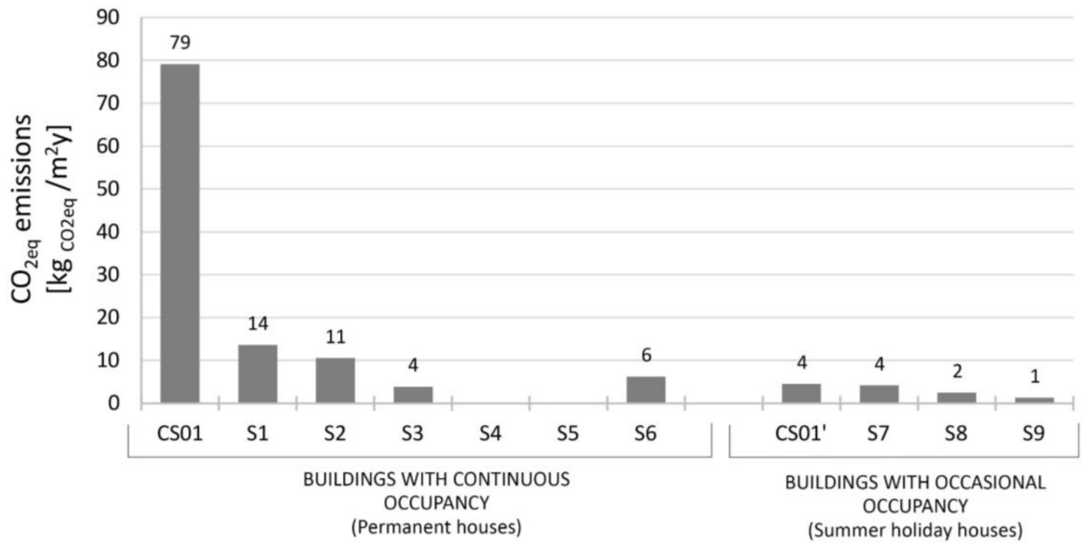


Figure 63. Annual CO_{2eq} emissions for Archetype 1

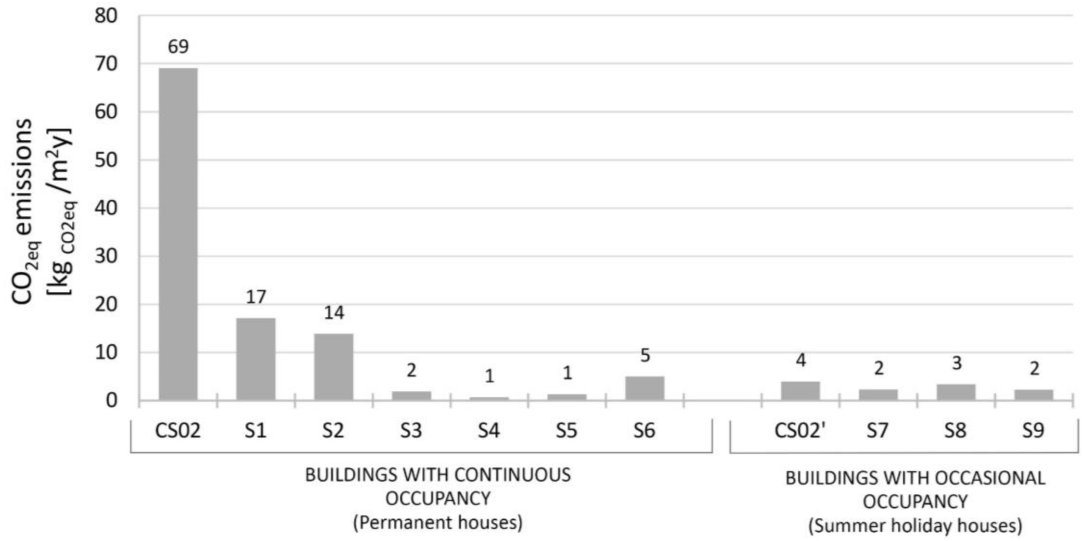


Figure 64. Annual CO_{2eq} emissions for Archetype 2

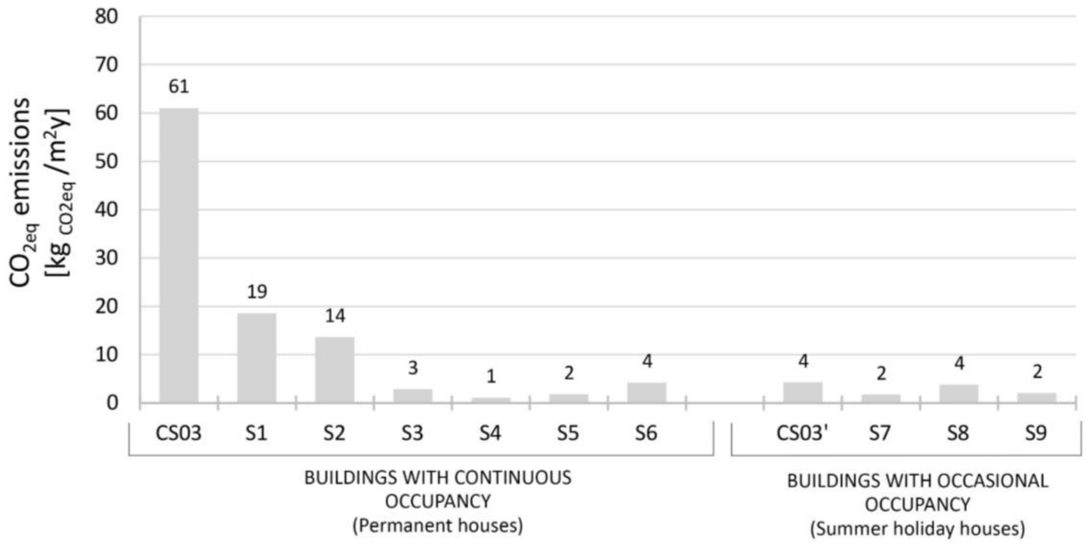


Figure 65. Annual CO_{2eq} emissions for Archetype 3

ESTIMATED SAVINGS

To highlight the energy savings achievable thanks to the retrofit interventions, Figures 66, 67 and 68 are reported, showing the savings for the three archetypes in terms of electricity consumption, total primary energy consumption with national conversion factors and with local factors, respectively.

Similarly, Figures 69 shows the CO_{2eq} emissions savings percentage for retrofit scenarios for the three archetypes.

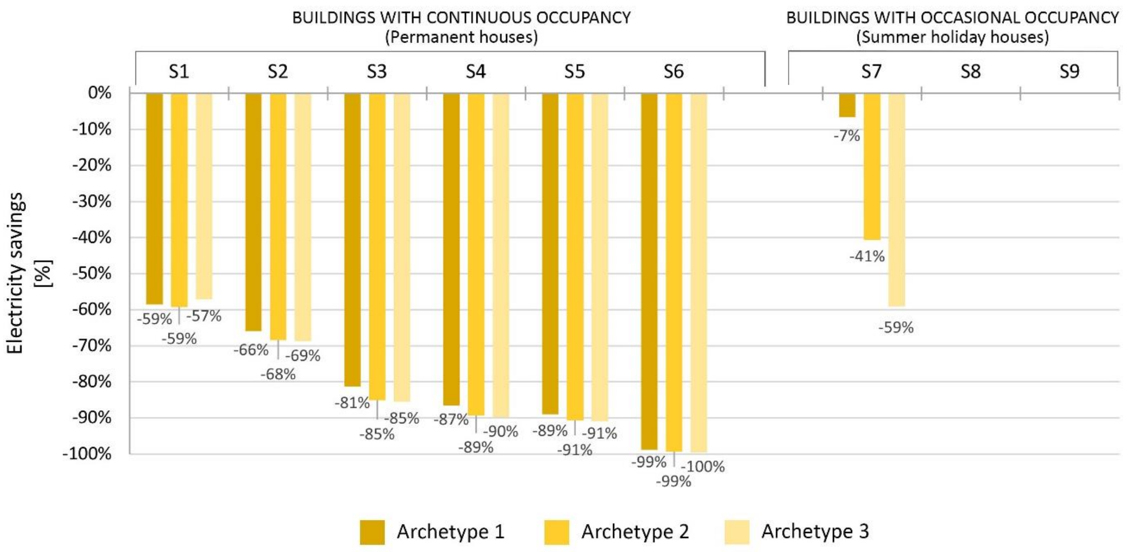


Figure 66. Electricity savings percentage

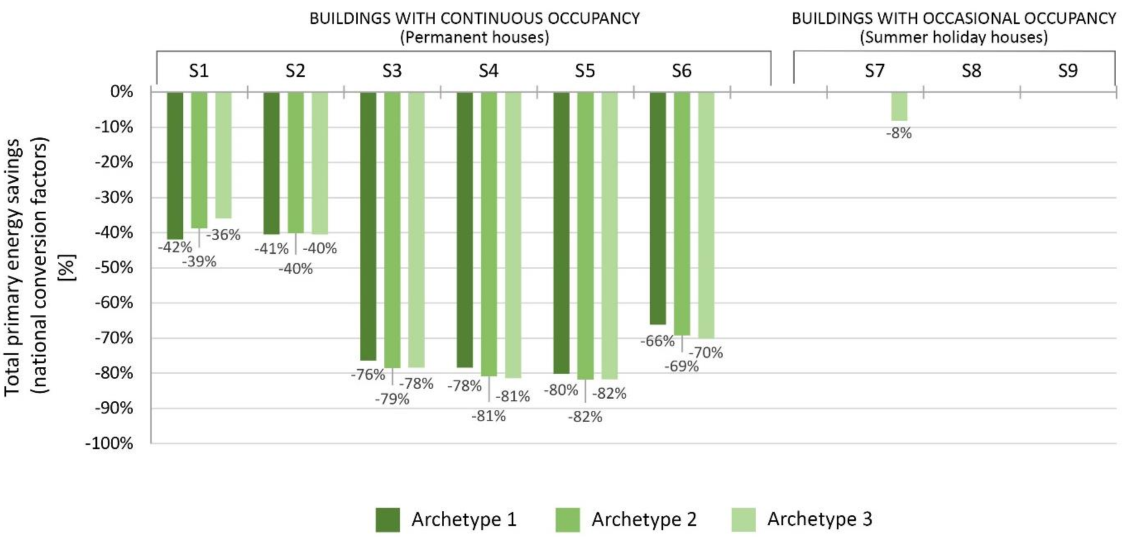


Figure 67. Total primary energy savings percentage calculated with national conversion factors

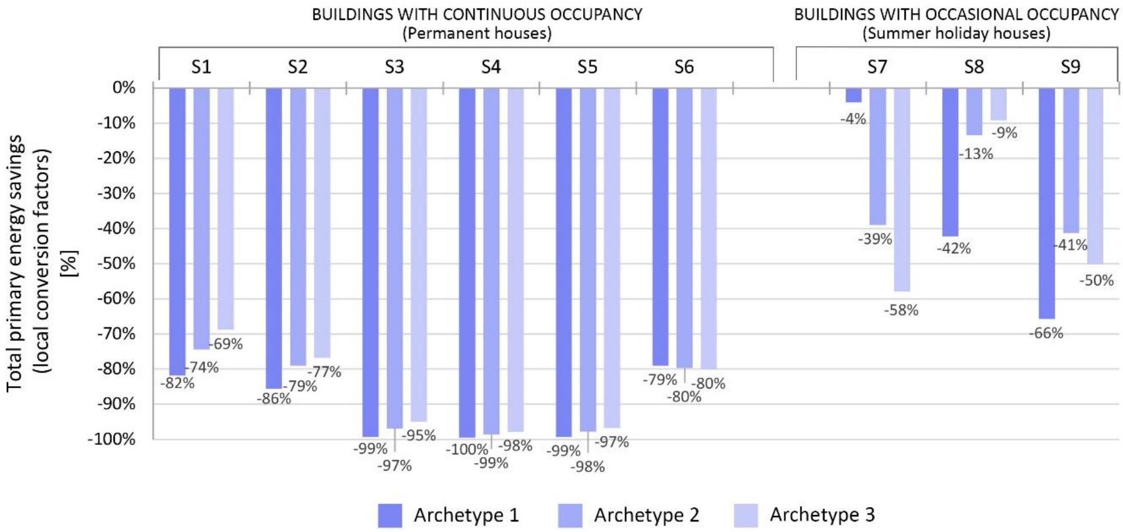


Figure 68. Total primary energy savings percentage calculated with local conversion factors

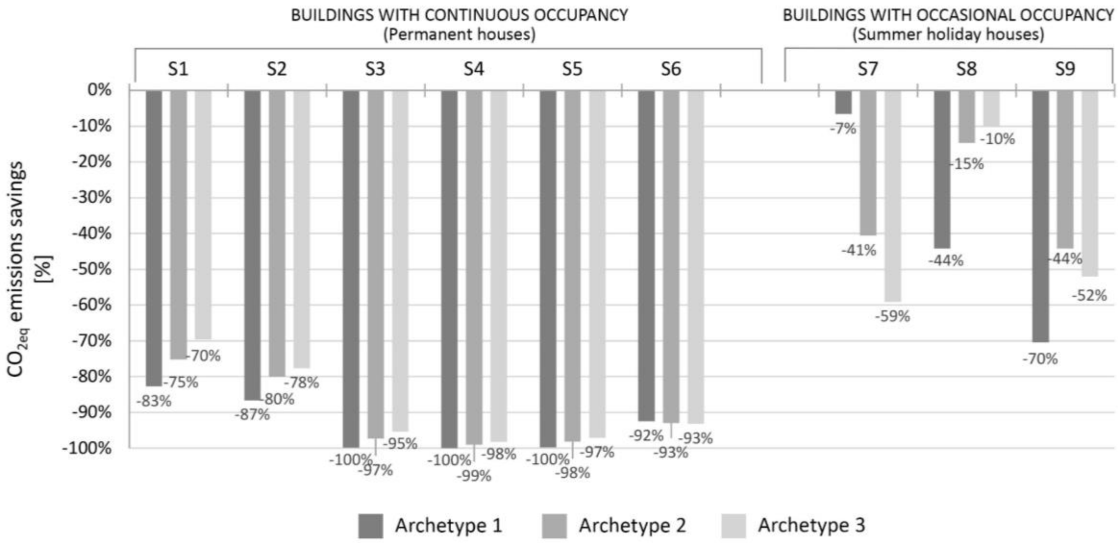


Figure 69. CO_{2eq} emissions savings percentage

5.4.1 Results discussion

Based on the analysis of retrofit scenarios results, described in the previous paragraph, the results discussion aims to deepen the following aspects:

1. The improvements in terms of energy and environmental performance achievable through energy retrofit, performing an estimation of the estimated savings in terms of electricity consumption, primary energy consumption and CO_{2eq} emissions, in line with the Mitigation Strategy.
2. The possible enhancement of *dammusi* building robustness and resilience levels, which results from the application of energy efficiency measures and strategies capable of improving these buildings properties against future uncertainties in

line with Adaption Strategy, which aims to prepare buildings to face inevitable future adversities. The results are qualitatively evaluated on the basis of specific studies findings, which are reported in detail in Paragraph 2.5.

QUANTITATIVE ASSESSMENT OF RETROFIT SCENARIOS WITH A VIEW TO DECARBONIZATION

The analysis of retrofit scenarios results for the three archetypes demonstrates the potential improvement of *dammusi* buildings energy and environmental performance deriving from the implementation of different energy efficiency measures related to building envelope, building systems and renewable energy sources.

First of all, looking at the bar charts previously reported, it is noticeable that retrofit scenarios S3, S4, S5, S6, which involve interventions on building envelope, present, in general, the lower consumptions and emissions and the higher savings. This is due to the cut in buildings energy demands for space heating and space cooling, arising from building envelope energy efficiency, which is in line with the first pillar set out by European energy efficiency strategy. Referring in particular to S5 and S6, interventions on *dammusi* buildings envelope can lead to an energy need for space cooling value lower than 15 kWh/m^2y, which meets Passive House Standard and, thus does not require energy systems for space cooling while ensuring occupants' thermal comfort. Since no systems for space cooling are present, therefore, related consumption and emissions are null. However, great consumptions and emissions reduction and good savings can be achieved even in those cases in which it is not possible or not convenient to intervene on buildings envelope; in such cases, the interventions concern only building systems, jointly with the eventual implementation of the use of on-site renewable energy sources according to the second and the first pillars set out by the European energy efficiency strategy. In this regard, it is interesting to observe results referred to retrofit scenarios S7, S8, S9, which are related to buildings with occasional occupancy. In particular, scenario S7 provides only the replacement of existing hot water storage heater for DHW production with a heat pump water heater with thermal storage. Despite the intervention is limited, it allows to obtain great savings in terms of electricity consumption, primary energy consumption and emissions, especially for buildings characterized by a high DHW consumption. In addition, it is interesting to note that scenarios S8 and S9, which includes the introduction of a multi-split heat pump for space cooling combined with PV system, differently from all other scenarios, do not entail savings in terms of electricity consumption and total primary energy consumption calculated with national conversion factors. This is because the introduction of a multi-split heat pump for space cooling implies higher consumptions than the current state, where no systems are present. As regards, instead, primary energy savings calculated with local factors, the same scenarios report savings values. In general, indeed, by reference to Figure 67 and Figure 68, it is noticeable that total primary energy savings calculated with local factors are higher than values calculated with national factors. Local conversion factors to primary energy for electricity, indeed, take into consideration the fact that about 98% of energy produced on the island derives from non-renewable sources. This stresses the importance of reducing the dependency on non-renewable energy sources on Pantelleria Island, starting from the cut in electricity consumption taken from the grid, which is mainly provided by diesel generators, through the implementation of the use of on-site renewable energy sources. To this end, solar systems are introduced in all scenarios related to buildings with continuous occupancy. In detail, a photovoltaic system is introduced in scenarios S1, S2, S3, S4, S5, while a solar thermal system is introduced in scenario S6, where a biomass boiler is involved. As it emerges from Figure 54, 55, 56, indeed, the introduction of PV system, combined with the installation of new efficient systems for space heating and space cooling, allows to have a great reduction of the total electricity consumptions and, particularly leads to a great saving of electricity taken from the grid. These electricity savings result in turn into primary energy savings and emissions savings, which meet the ambitious energy and emissions reduction targets set out for 2030 by European legislation, which aims to cut net GHG emission by at least 55% by 2030 compared to 1990 (EC, 2020). Scenario S6, involves a biomass boiler, so, in this case, the main energy source is not electricity but biomass; this solution is coupled with a solar thermal system, which allows to cover about 75% of annual domestic hot water production.

Therefore, decarbonization process for *dammusi* buildings can be pursued through different energy efficiency measures, which can be selected according to the current state of a specific existing *dammuso* building, to its constraints and to occupants needs and requirements. Results obtained for archetypes prove that by implementing a set of different energy efficiency measures at a building scale, remarkable cuts can be achieved in primary energy consumptions and GHG emissions due to the residential building sector.

QUALITATIVE ASSESSMENT OF RETROFIT SCENARIOS VITH A VIEW TO ROBUSTNESS AND RESILIENCE

Despite quantitative results are not provided for the assessment of *dammusi* buildings robustness and resilience levels enhancement, some general outcomes can be drawn on the basis of specific studies results found in literature and described in Paragraph 2.5. The implementation of different energy efficiency measures for each retrofit scenario, as well as improving *dammusi* buildings energy and environmental performance, can enhance their robustness and/or resilience levels.

Firstly, according to different studies, a high performing envelope can, on the one hand, provide higher robustness to climate change effects (e.g., increasing external temperatures), and, on the other hand, assure more acceptable thermal conditions in case of interruptions in building systems services. Since Pantelleria Island could be especially affected by global warming effects, the increase of external air temperatures will impact on *dammusi* buildings energy performance and on their occupants' comfort, especially during the summer season. Therefore, the performance of retrofit scenarios which involve energy measure on *dammusi* envelope (S3, S4, S5, S6) may be less sensitive to raising external temperatures, even if, conceivably, building energy needs for space cooling will increase, while needs for space heating will decrease. Furthermore, these retrofit scenarios present a lower overheating risk in summer months, potentially due to cooling systems interruptions caused by power outages. Beside intervention on building envelope, robust and resilience levels of *dammusi* buildings can be improved through the replacement of existing energy systems with more efficient ones and through the deployment of on-site renewable energy sources towards high buildings self-sufficiency. Indeed, efficient and electricity- based systems can support building resilience in case of possible atypical operation conditions due to unexpected events, especially when combined with renewable energy sources or batteries. Moreover, the replacement of existing *dammusi* building systems, electric heaters, and hot water storage heaters, with heat pumps, can guarantee a higher robustness of the performance in case of foreseeable events (e.g., changes in occupants' habits, increase of external air temperatures, etc.). For this reason, all retrofit scenarios proposed for *dammusi* buildings, with the sole exception of the scenario S6, include the introduction of heat pumps for space heating, space cooling and/or DHW production. Furthermore, in most retrofit scenarios, excluding S6 and S7, PV system is introduced. In case of buildings with continuous occupancy, from scenario S1 to S5, a battery storage is also combined. These scenarios, therefore, are the most resilient in case of power failure, being able to guarantee a higher self-sufficiency level. In these cases, *dammusi* buildings, reducing their dependence on external energy sources, would be able to provide continuous minimum services to occupants thanks to the use of renewable sources and storage systems.

In the light of above, it can be concluded that scenarios S4 and S5 are those making *dammusi* the most robust and resilient. In fact, these scenarios involve combined interventions on *dammusi* building envelope and the replacement of existing energy systems with heat pumps for space heating and DHW production (S5) or for space heating, space cooling and DHW production (S6). Furthermore, in both cases, PV system and electricity battery storage are introduced. All other retrofit scenarios, by intervening only on some aspects, can enhance *dammusi* buildings robustness and resilience levels, but in a limited way.

In addition to retrofit interventions that can be proposed for *dammusi* buildings during the initial design phase, occupants' choices during the operational and management phase can contribute to enhance *dammusi* buildings robustness and resilience. According to different studies, indeed, household lifestyles and preferences can substantially affect both buildings energy and environmental performance and their robustness and resilience. Conscious occupants' choices, such as appropriate set-points temperature for cooling and heating, can increase robustness in terms of energy performance and thermal comfort. Furthermore, given the current societies dependency on energy services, the household resilience in terms of energy efficiency, energy sufficiency and flexibility can support *dammusi* resilience against future energy uncertainties, caused by potential natural extreme events or geopolitical changes.

6. Conclusions and future developments

The consequences of the unavoidable climate change the world is experiencing ask for an urgent transition towards carbon neutral energy systems. Buildings, and especially existing buildings, which are recognized among the main causes of climate change, will inevitably be affected by future uncertain events.

To respond to the existing challenges, there is the need to intervene on the building stock with a view to both mitigation and adaption strategies. On the one side, it is fundamental to reduce the environmental impact of buildings (towards the decarbonization of the sector), increasing their energy efficiency and introducing carbon-neutral energy systems; on the other side, buildings should be re-thought and equipped with systems helping them to cope with diverse foreseeable and unforeseeable events that could occur in future (mostly as a consequence of climate change), aiming to increase their robustness and resilience.

As described in Chapter 1, the building sector decarbonization has become a central element in policy discussions and is mainly correlated to energy efficiency, electrification of final uses and integration of renewable energy sources. Conversely, lower attention is dedicated to robustness and resilience features, despite their importance in making buildings prepared against future inevitable occurrences. Deepening this aspect, Chapter 2 has proposed a literature review on the main definitions and features of robustness and resilience, trying to tailor these concepts at the building level by collecting and comparing specific literature studies; moreover, part of the review has focused on the possible strategies of building design and/or retrofit capable of enhancing the robustness and resilience of buildings.

If these considerations can be easier for new constructions, it is well known that existing buildings represent the majority of the building stock, asking for new efforts to designers and professionals in identifying proper strategies to improve their conditions in the view of both decarbonization and robustness/resilience objectives.

In the light of the above, the thesis focuses on existing buildings, aiming to explore and compare possible retrofit strategies, in the light of the three main goals of the future buildings (i.e., sustainability, robustness and resilience). The thesis concentrates on the particular geographical context of Pantelleria Island, which set particularly ambitious targets to complete decarbonization process of the island, and on its traditional building heritage, mostly constituted by typical *dammusi* buildings. By defining a set of *dammusi* archetypes, chosen based on their frequency in the stock, their current energy needs and consumptions were assessed, and alternative strategies of energy retrofit were identified, in line with the existing regulatory constraints for the protection of the historical and architectural heritage of the island. Retrofit scenarios results, deriving from quasi steady-state energy simulations through Edilclima software, were compared to explore their capability in reducing the environmental impact of the *dammusi* and in improving the *dammusi* robustness to future uncertainties. The analysis of the results has highlighted how the implementation of retrofit solutions can provide remarkable cuts of *dammusi* buildings consumptions and emissions and, at the same time, enhance *dammusi* buildings robustness and resilience levels. The strategies involving a complete retrofit of the archetypes and the integration of renewable energy sources were identified as the most effective for the transition of the stock towards decarbonization and adaptation. Indeed, the thesis aimed to emphasize how the implementations of strategies required to meet buildings decarbonization goals, as expected by Mitigation Strategy, can often improve also buildings robustness and resilience, as intended by Adaption Strategy. The thesis contributed to highlight that despite there is still a long way to reach the ambitious goals for the sector, buildings have to meet all future challenges (decarbonization, robustness and resilience) in order to both contribute to making impacts of climate change less severe and be prepared to face consequences resulting from these same impacts. A coordinated and holistic approach to building retrofit is required, having in mind that future buildings must be capable of coping with diverse foreseeable and unforeseeable events, which are exacerbated in number and intensity by the evident climate change phenomena.

The thesis opens the way to further developments and insights. Despite energy and environmental savings deriving from retrofit solutions implementation are estimated, no economic assessment was developed, even though it is a fundamental aspect in this field. Furthermore, only a qualitative evaluation of robustness and resilience enhancement was performed when comparing the retrofit solutions. Future work could be developed in order to provide a quantitative assessment of these aspects. For instance, *dammusi* buildings robustness assessment could be carried out by varying external climate conditions (to simulate the increment of external air temperature due to climate change consequences) in the energy simulations, evaluating their performance sensitivity in terms of energy or environmental consumptions. In addition, building resilience to energy supply interruptions due to extreme natural events could be quantitatively evaluated through energy simulations, analysing the capability of on-site renewable systems and batteries in guaranteeing the continuation of minimum heating, cooling or DHW services, maintaining internal conditions of thermal comfort to an acceptable level.

Nomenclature

ACH: Air Changes per Hour

ASHP: Air Source Heat Pump

BE: Building Envelope

BIPV: Building Integrated Photovoltaics

BS: Building Systems

C: Pooling

CNR-IIA: Consiglio Nazionale delle Ricerche – Istituto sull'Inquinamento Atmosferico

CO_2: Carbon Dioxide

CO_{2eq}: Equivalent Carbon Dioxide

COP: Coefficient of Performance

COP: Conferences of the Parties

CS: Current State

D: Door

DHW: Domestic Hot Water

DM: Decreto Ministeriale

DOE: Department of Energy

DP: Decreto Presidenziale

DPR: Decreto del Presidente della Repubblica

EC: European Commission

ECBCS: Energy Conservation in Buildings and Community Systems

EEA: European Environmental Agency

EEM: Energy Efficiency Measure

EER: Energy Efficiency Ratio

EGP: Enel Green Power

ENEA: Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

EU: European Union

GHG: Greenhouse Gases

GSHP: Ground Source Heat Pump

H: Heating

IEA: International Energy Agency

IPCC: Intergovernmental Panel on Climate Change

LCC: Life Cycle Cost

LCEI: Life Cycle Environmental Impact

M: Wall

NESOI: New Energy Solutions Optimised for Islands

NZEB: Nearly Zero Energy Building
P: Ground
PNIP: Ente Parco Nazionale Isola di Pantelleria
PRG: Piano Regolatore Generale
PV: Photovoltaic
PVGIS: Photovoltaic Geographical Information System
RS: Renewable Sources
S: Roof (Paragraph 5.1)
S: Scenario (Paragraph 5.3, Chapter 6)
UNEP: United Nations Environment Programme
UNFCCC: United Nations Framework Convention on Climate Change
UNI: Ente Italiano di Normazione
W: Window

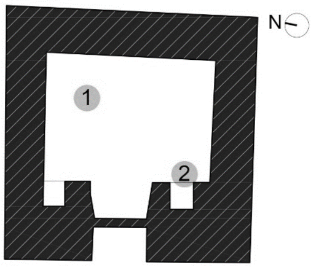
Appendix

Abacus of *dammusi* buildings typologies

Tipologia	**DAMMUSO MONOCELLULA**
Descrizione	"Il dammuso come ricovero è costituito da un mono-ambiente e può avere forma quadrata o rettangolare, con un solo vano di accesso; accanto vi si può trovare la cisterna che raccoglie l'acqua piovana. Sono principalmente presenti in quei luoghi più distanti dai centri abitati" (Giardina, 2018).

Rappresentazioni e schemi funzionali

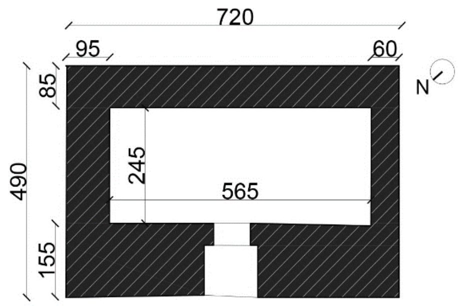
PIANTA TIPO CON FUNZIONI



Funzioni

1- Locale per attrezzi agricoli
2 - Nicchia (*kaséna*)

DIMENSIONI TIPO



Numero locali: **1**
Superficie media: **10-20 m²**
Frequenza sul territorio: **Bassa**

ULTERIORI RAPPRESENTAZIONI

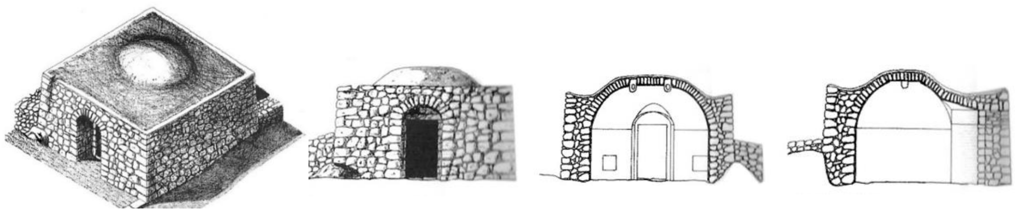


Figura 1: Assonometria, prospetto e sezioni di un dammuso monocellula tipo da De Giovanni (1998)

Documentazione fotografica

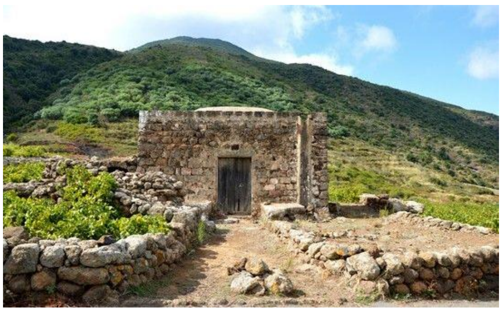


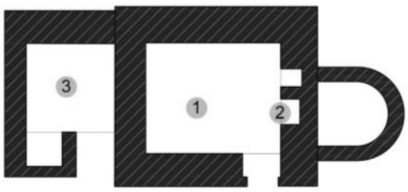
Figura 2: Esterno di un dammuso monocellula tipo non ristrutturato
www.viverepantelleria.it

Figura 3: Interno di un dammuso monocellula tipo ristrutturato
www.pantellerialink.it

Tipologia	DAMMUSO DOPPIA CELLULA
Descrizione	“Il dammuso come ricovero presenta un altro ambiente adibito a stalla o a cucina” (Giardina, 2018).

Rappresentazioni e schemi funzionali	Documentazione fotografica

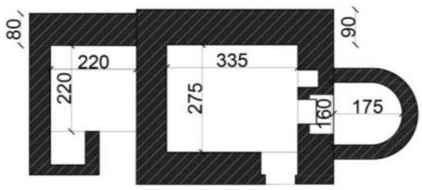
PIANTA TIPO CON FUNZIONI



Funzioni

1- Locale per attrezzi agricoli
2 - Nicchia (*kaséna*)
3- Stalla o cucina

DIMENSIONI TIPO



Numero locali: **2**
Superficie media: **20-30 m²**
Frequenza sul territorio: **Media**

Figura 4: Esterno di un dammuso doppia cellula tipo non ristrutturato da www.conoscerepantelleria.it

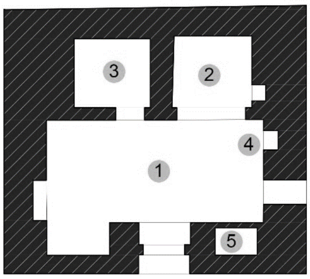
Figura 5: Esterno di un dammuso doppia cellula tipo non ristrutturato da www.conoscerepantelleria.it

Figura 6: Esterno di un dammuso doppia cellula tipo ristrutturato da www.istockphoto.com

Tipologia	DAMMUSO TRIPARTITO
Descrizione	“Il dammuso come abitazione stagionale è composto da un vano principale, solitamente rettangolare e comunicante con due ambienti più piccoli, l’*alcova* riservata ai coniugi e separata dall’ambiente principale con una tenda e il *cammarino,* un ambiente più piccolo che ospitava la camera da letto dei figli” (Giardina, 2018).

Rappresentazioni e schemi funzionali

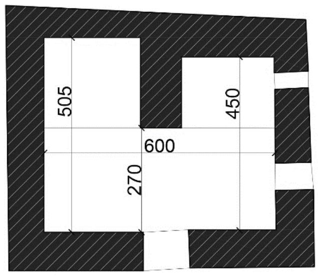
PIANTA TIPO CON FUNZIONI



Funzioni

1- Camera (*kammira*)
2- Camera da letto (*arkova*)
3- Piccola stanza (*kammarinu*)
4- Nicchia (*kasèna*)
5- Palmento (*palmèntu*)

DIMENSIONI TIPO



Numero locali: **3**
Superficie media: **40-55 m²**
Frequenza sul territorio: **Media**

ULTERIORI RAPPRESENTAZIONI

Figura 7: Sezione e prospetto di un dammuso tripartito tipo da www.buildlab.it

Documentazione fotografica

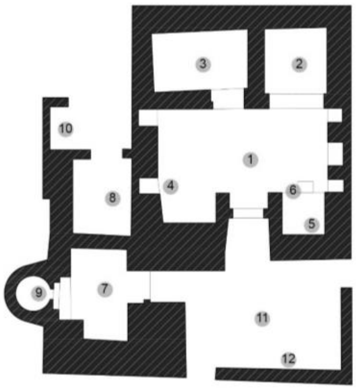
Figura 8: Esterno di un dammuso tripartito tipo non ristrutturato da www.conoscerepantelleria.it

Figura 9: Interno di un dammuso tripartito tipo non ristrutturato da www.conoscerepantelleria.it

Tipologia	DAMMUSO PER AGGREGAZIONE COMPLESSA
Descrizione	“Il dammuso a carattere permanente è molto più complesso perché oltre al nucleo costituito dal vano principale, dall’alcova e dal cammarino, si arricchisce di altre appendici che lo rendono più articolato: l’aia, il magazzino, le stalle, il forno, il *parmentu.* La cucina è sempre indipendente e ha l’accesso dal terrazzo. Nelle immediate vicinanze si trova la cisterna per la raccolta delle acque” (Giardina, 2018).

Rappresentazioni e schemi funzionali

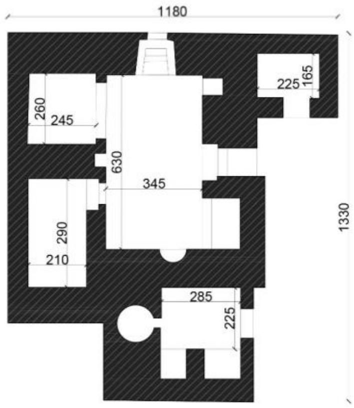
PIANTA TIPO CON FUNZIONI



Funzioni

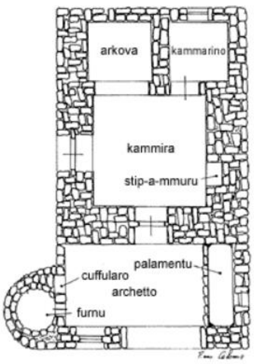
1- Camera (*kammira*)	7- Cucina (*kucina*)
2- Camera da letto (*arkova*)	8- Stalla (*staddra*)
3- Piccola stanza (*kammarinu*)	9- Forno a legna (*furnu*)
4- Nicchia (*kasèna*)	10- Mangiatoia (*mancatura*)
5- Palmento (*palmèntu*)	11- Terrazzo (*passiaturi*)
6- Vasca di raccolta (*palaturi*)	12- Sedile in muratura (*dukkena*)

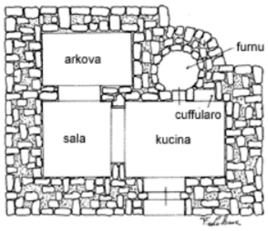
DIMENSIONI TIPO



Numero locali: **4-6**
Superficie media: **150-250 m^2**
Frequenza sul territorio: **Alta**

ULTERIORI RAPPRESENTAZIONI





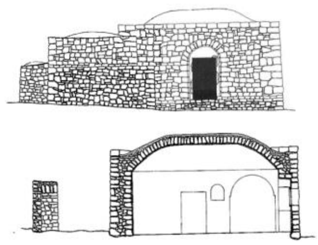


Figura 10: Piante tipo di dammusi per aggregazione complessa da www.buildlab.it; prospetto e sezione di un dammuso per aggregazione complessa tipo da De Giovanni (1998)

Documentazione fotografica

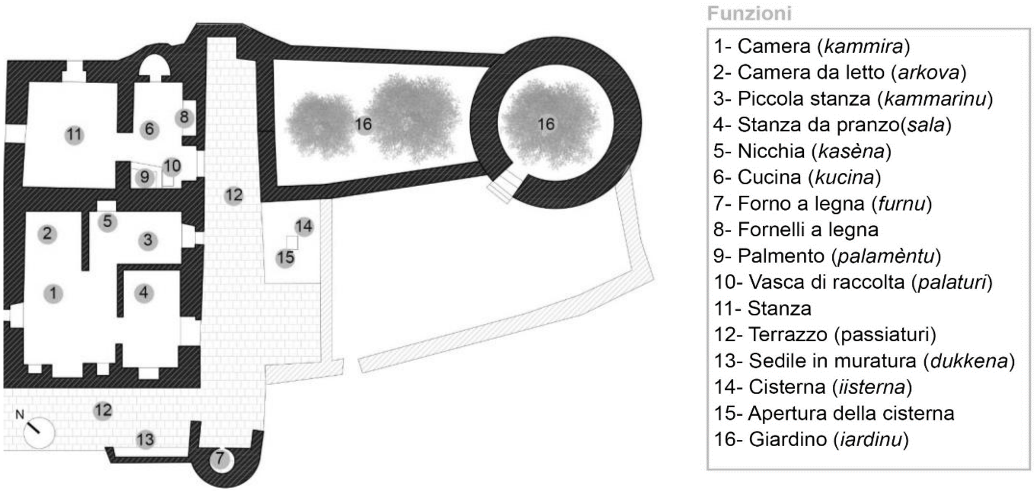
Figura 11: Esterno di un dammuso per aggregazione complessa ristrutturato da www.abitarepantelleria.it

Figura 12: Interno del nucleo di un dammuso per aggregazione complessa ristrutturato da www.abitarepantelleria.it

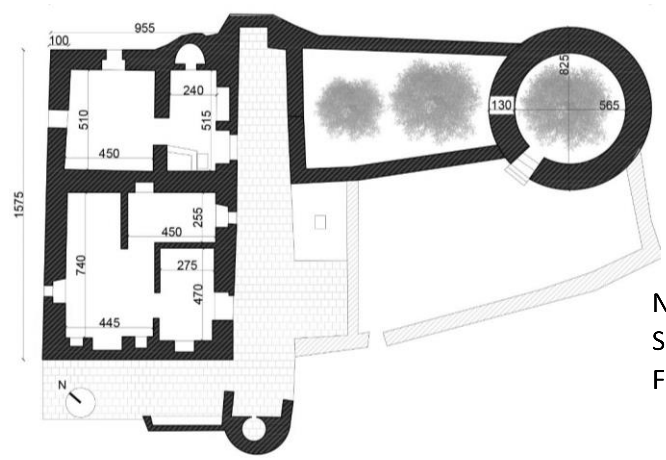
Tipologia	DAMMUSO PER AGGREGAZIONE COMPLESSA CON ELEMENTI ACCESSORI E PERTINENZE
Descrizione	“Il dammuso può essere accompagnato dal giardino pantesco, una struttura indipendente di forma tronco-conica, realizzata in pietra a secco e priva di copertura. Accessibile mediante un piccolo ingresso, la struttura accoglie uno o due alberi di agrumi. L’alto muro di recinzione protegge dagli intensi e frequenti venti, fornendo allo stesso tempo il giusto grado di ombreggiamento” (Stara, 2013).

Rappresentazioni e schemi funzionali

PIANTA TIPO CON FUNZIONI



DIMENSIONI TIPO



Numero locali: **7-15**
Superficie media: **300-350 m^2**
Frequenza sul territorio: **Media**

Documentazione fotografica

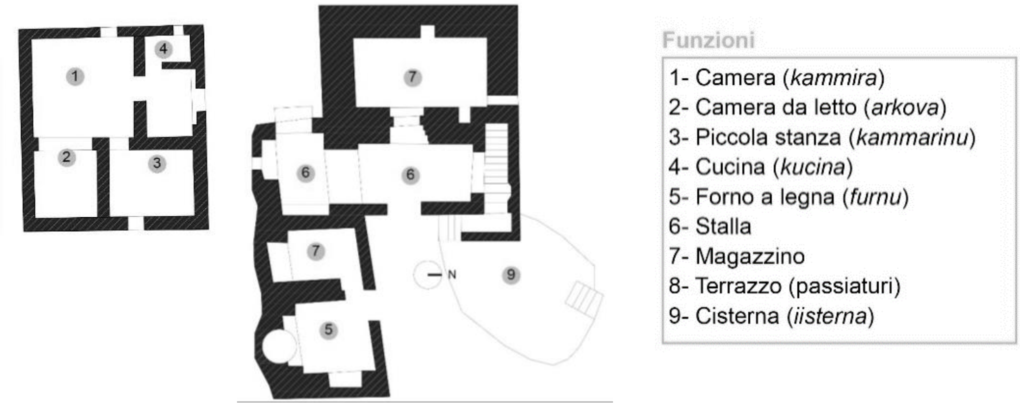
Figura 13: Dammuso con giardino pantesco annesso da www.dammuso.org

Figura 14: Giardino pantesco tipo da www.visitpantelleria.it

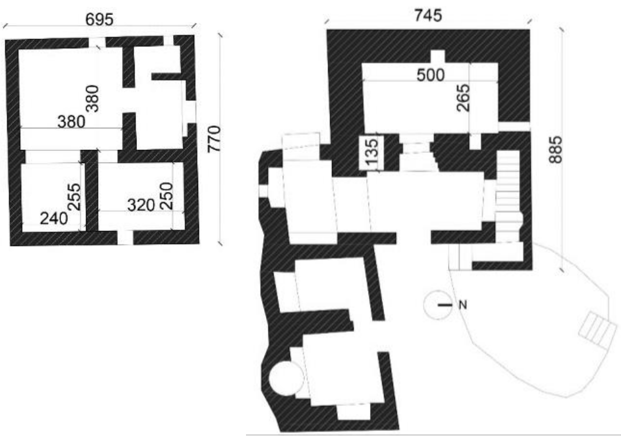
Tipologia	DAMMUSO PALAZZETTO
Descrizione	“Il palazzotto rappresenta l’evoluzione tipologica del dammuso e si presenta come una struttura a due livelli che si trova in zone prettamente agricole. Lo sviluppo verso l’alto di questi sistemi costruttivi era un simbolo del benessere economico raggiunto dalle famiglie proprietarie. Le planimetrie sono differenti pur ritrovando sistemi di ambienti invarianti, come il complesso camera-*cammarino*-*alcova*. Attorno al palazzotto erano generalmente collocati ambienti funzionali all’attività agricola o allevamento, come magazzini e stalle. La più alta concentrazione di palazzetti si ha nelle aree intorno alla cittadina di Pantelleria” (Scarano, 2007).

Rappresentazioni e schemi funzionali

PIANTA TIPO CON FUNZIONI



DIMENSIONI TIPO



Numero locali: **5-7**
Superficie media: **200-250 m²**
Frequenza sul territorio: **Bassa**

Documentazione fotografica

Figura 15: Esterno di un palazzetto tipo non ristrutturato da Scarano (2007)

Figura 16: Interno di un dammuso palazzetto ristrutturato da www.pantelleriaisland.it

Abacus of *dammusi* buildings components

"Il dammuso è un fabbricato rurale realizzato in pietra e le sue caratteristiche architettoniche più particolari sono la sua struttura cubica realizzata a secco e la sua copertura a cupola. L'orientamento è tale da offrire la minor superficie al vento dominante, il maestrale, proveniente da nord-ovest" (Giardina, 2018).

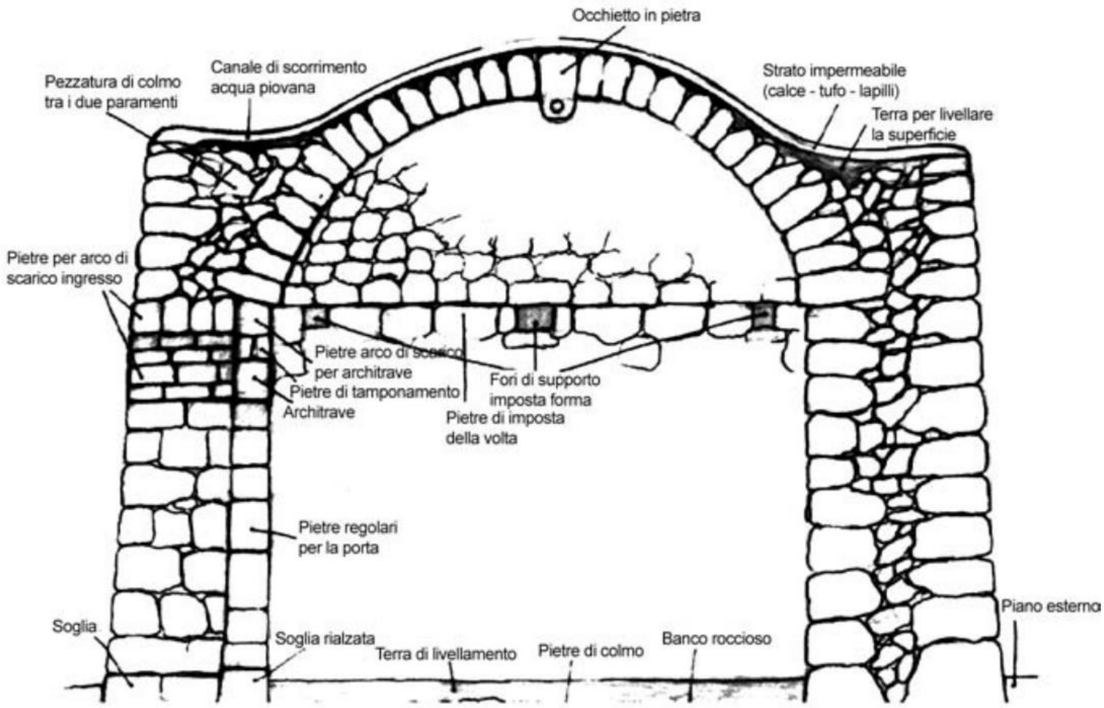


Figura 17: Sezione schematica di un dammuso di Pantelleria da Fiorito (2009)

Elemento tecnologico	**CHIUSURA OPACA VERTICALE** ***Struttura***
Descrizione	“I muri venivano realizzati ***a casciata*, a cassa**, cioè composta da due file parallele di pietre una esterna e l’altra interna e riempimento della sacca interna con pietrisco di piccole dimensioni e terra rossa. Le costruzioni originarie erano realizzate totalmente **a secco**, contrariamente ai modelli cronologicamente successivi (tra il 1700 e il 1950), nei quali si ricorreva a **leganti** quali calce, pozzolana o terra. Intorno agli anni 1940-1950 i dammusi cominciarono ad essere costruiti con la tecnica della muratura in **pietra tagliata**. Oggi il blocchetto di pomice e il calcestruzzo hanno del tutto soppiantato la pietra tagliata che funge solo più da rivestimento” (Scarano, 2007).
Dimensioni	Spessore: muri in pietra tagliata 38 cm, muri a cassa tra 0,8 m e 2 m Altezza media muratura esterna: 3 m Altezza media muratura interna: 1,8 m (imposta della volta) Inclinazione verso l’interno della parete: 10- 15% Dimensioni pietre di riempimento: dai 3 ai 15 cm Dimensioni pietre portanti: dai 15 ai 70 cm

Vincoli normativi

Piano Territoriale Paesistico dell’isola di Pantelleria Norme di Attuazione, Decreto 26.07.2000

CONSENTITO
Ampliamenti: Consentiti limitati ampliamenti volumetrici nel rispetto della cubatura consentita ed esclusivamente finalizzati alla creazione di piccoli servizi igienici o di pertinenze di limitate dimensioni, che non modifichino morfologia e tipologia dei luoghi e rispettino caratteristiche tipologiche e cromatiche dell’impianto originario.

Apertura varchi: Consentito aprire nuove porte e finestre delle dimensioni minime necessarie e di forma tradizionale (quadrata o rettangolare). Nelle pareti in pietra a faccia vista le nuove aperture devono essere realizzate con pietra "tagliata".

NON CONSENTITO
Alterazioni strutturali: Non è consentito alterare lo schema della struttura muraria, suddividere le stanze con copertura a volta, ridurre in modo sistematico i muri portanti e realizzare seconde elevazioni.

Piano Regolatore Generale del Comune di Pantelleria, Norme Tecniche di Attuazione, integrate al 16.09.2014, Capitolo II, art.4 - art. 5

CONSENTITO
Ampliamenti: Deve essere conteggiata la sola superficie utile calpestabile per il calcolo della cubatura realizzabile.
Nel concetto di superficie calpestabile non rientrano gli armadi a muro, nicchie e quant’altro ricavato all’interno dello spessore dei muri e sollevato da terra per almeno dieci centimetri. Non rientrano altresì l’apertura dei varchi di collegamento tra l’immobile esistente e la parte in ampliamento.

Recupero di ruderi: Nel caso di recupero di ruderi il fabbricato deve essere accatastato, e nella riedificazione, qualora non fosse possibile verificare la consistenza, i muri perimetrali, all'interno della sagoma catastale del solo fabbricato, vengono realizzati con spessore non inferiore a cm. 70 comprensivi di rivestimento in pietra.

Spazi interni: È possibile realizzare vani alcova della dimensione minima di mt. 2,50 x 2,50 privi di finestratura a condizione che siano collegate con un vano soggiorno tramite apertura ad arco della larghezza minima di mt. 1,80 priva di infisso.
Nel caso di realizzazione di bagni interni che utilizzano vani esistenti (camerini o alcove) senza necessità di demolire la volta di copertura, potranno non essere realizzati gli antibagni, a condizione che venga potenziata l'areazione naturale con l'ausilio di un sistema di areazione forzata.

Documentazione fotografica

Figura 18: Struttura muraria interna a secco da www.conoscerepantelleria.it

Figura 19: Struttura muraria esterna a secco da www.ildammuso.com

Figura 20: Struttura muraria esterna con pietra e legante da www.gualtieroturati.it

Figura 21: Struttura muraria esterna con pietra e legante da www.pantellerialink.it

Figura 22: Struttura muraria in laterizio con rivestimento esterno in pietra di un dammuso di nuova costruzione da www.abitarepantelleria.com

Figura 23: Dettaglio costruttivo di un dammuso contemporaneo, con tamponatura interna in laterizio, doppio strato di blocchi in pietra regolare e rivestimento con pietra grezza da www.progettarebioedile.it

Elemento tecnologico	CHIUSURA OPACA VERTICALE ***Finitura di facciata***
Descrizione	"Il dammuso-abitazione aveva sempre la **facciata principale intonacata**, a differenza del *sardune* o del dammuso di campagna, lasciati grezzi a pietra viva. A volte le pareti esposte a sud venivano intonacate all'esterno con strati successivi di calce e sabbia o calce e pomice per ridurre ulteriormente l'assorbimento solare. Le facciate possono essere in **pietra a vista**, tra cui la pietra lavica, assumendo colori vari, dal nero a toni più chiari. Nelle costruzioni odierne, la pietra ha solo il ruolo di rivestimento esterno" (Giardina, 2018).

Vincoli normativi

Piano Territoriale Paesistico dell'isola di Pantelleria Norme di Attuazione, Decreto 26.07.2000

NON CONSENTITO

Alterazione dei prospetti: non è consentito realizzare rivestimenti estranei alla tipologia locale (marmi e mattoni), costruire merlature sui prospetti o a recinzione di terrazze, intonacare le facciate in pietra a vista.

Piano Regolatore Generale del Comune di Pantelleria, Norme Tecniche di Attuazione, integrate al 16.09.2014, Capitolo II, art.4 - art. 5

CONSENTITO

Prospetti: al di fuori dei centri abitati e dei nuclei, i prospetti devono essere rivestiti in pietra con forma irregolare ed *acquintati* (muri a due facce), gli spigoli e le aperture devono essere realizzati con pietre squadrate, così pure gli architravi.

Ambienti interni: i locali dei *Sardune* possono essere intonacati all'interno, pavimentati e dotati di porta - finestra in legno secondo le dimensioni tipiche e possono avere altezze inferiori a quelle previste alle norme vigenti in materia.

Documentazione fotografica

Figura 24: Dammuso con facciata sud intonacata da www.pantellerialink.it

Figura 25: Dammuso con facciata in pietra a vista da www.pantellerialink.it

<table>
<tr><td rowspan="2">Elemento tecnologico</td><td>CHIUSURA OPACA SUPERIORE</td></tr>
<tr><td>Volta strutturale</td></tr>
<tr><td>Descrizione</td><td>“Tutti gli ambienti del dammuso sono voltati e le volte possono essere a botte, a botte lunettate o a crociera. La volta a botte è la forma primordiale di copertura ed era utilizzata per racchiudere superfici rettangolari, quelle a crociera per gli ambienti a pianta quadrata. Successivamente quando si perfezionò la tecnica, nei dammusi di grandi dimensioni si adoperò la volta a botte lunettata o la volta reale; in genere le lunette sovrastano le aperture quando la quota dell’imposta è molto bassa. Nelle volte dei piani superiori dei palazzotti a due piani, venivano costruite con pietre più leggere” (Giardina, 2018).</td></tr>
<tr><td>Dimensioni</td><td>Altezza di imposta della volta: 1,8 m
Spessore della pietra per realizzazione volta: 25-30 cm
Spessore totale copertura: 30-40 cm
Sporgenza: 50 cm</td></tr>
<tr><td colspan="2">Vincoli normativi</td></tr>
<tr><td colspan="2"><u>Piano Territoriale Paesistico dell’isola di Pantelleria Norme di Attuazione, Decreto 26.07.2000</u>

NON CONSENTITO
Alterazione degli ambienti interni: non è consentito suddividere le stanze con copertura a volta e controsoffittare le volte.

<u>Piano Regolatore Generale del Comune di Pantelleria, Norme Tecniche di Attuazione, integrate al 16.09.2014, Capitolo II, art.4 - art. 5</u>

NON CONSENTITO
Alterazione degli ambienti interni: è vietato suddividere con tramezzatura i vani esistenti coperti a volta, salvo che per le volte a botte.

CONSENTITO
Interventi sulle volte: nei dammusi esistenti coperti, dovranno essere conservati le strutture a volta preesistenti. Sono ammesse demolizioni e ricostruzioni delle volte solo in presenza di una perizia di un tecnico strutturista che dichiari l’impossibilità del recupero con semplici opere di consolidamento, corredando la richiesta con i calcoli di verifica statica della volta stessa.
Se per motivi statici risulta necessario demolire e ricostruire la copertura, in tal caso, la stessa dovrà essere ricostruita dotando ogni singolo vano di volta.</td></tr>
</table>

Documentazione fotografica

Figura 26: Locale ristrutturato con volta a botte da www.conoscerepantelleria.it

Figura 27: Locale ristrutturato con volta a botte da www.solopantelleria.com

Figura 28: Locale ristrutturato con volta a crociera da www.conoscerepantelleria.it

Figura 29: Locale ristrutturato con volta a crociera da www.solopantelleria.com

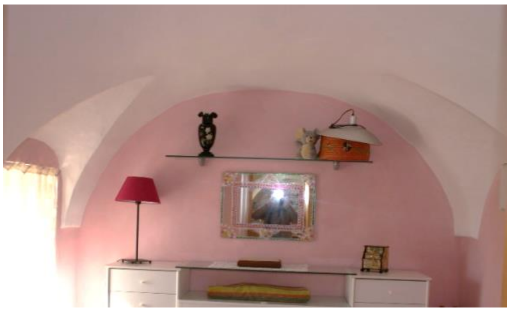


Figura 30: Locale ristrutturato con volta a botte lunettata da www.conoscerepantelleria.it

Figura 31: Locale ristrutturato con volta a botte lunettata da www.sicilyluxuryvillas.com

Figura 32: Locale ristrutturato con volta reale da www.conoscerepantelleria.it

Figura 33: Locale ristrutturato con volta reale da www.pantelleriacharme.it

Elemento tecnologico	**CHIUSURA OPACA SUPERIORE** ***Finiture della copertura***
Descrizione	"Nei primi dammusi la finitura della copertura era realizzata in **malta di terra e acqua** e l'impermeabilizzazione era assicurata dalla ricrescita sulla cupola dello stesso tipo di **vegetazione** spontanea del suolo; nel periodo successivo, nell'esecuzione della tecnica di **impermeabilizzazione** si procedeva ad addossare sullo strato di terra battuta che serviva per modellare la sagoma della volta uno strato battuto realizzato con un **impasto di calce, tufo e lapilli vulcanici**. I roveri degli animali e il magazzino possono presentare una copertura vegetale (rami, arbusti, canne) e uno strato di terra" (Giardina, 2018). "Negli spazi abitativi la superficie interna della cupola presentava una **finitura in intonaco** stesa su un **fondo** realizzato con un impasto di **calce e sabbia.** Nelle strutture adibite a stalla o magazzino, l'interno della cupola viene lasciato in **pietra a vista**" (Scarano, 2007).
Dimensioni	Spessore totale copertura: 30-40 cm Spessore strato di calce: 5 cm

Documentazione fotografica

Figura 34: Volta interna intonacata da www.abitarepantelleria.it

Figura 35: Volta interna in pietra grezza da www.conoscerepantelleria.it

Figura 36: Finitura esterna della copertura da www.conoscerepantelleria.it

Figura 37: Finitura esterna della copertura da www.solopantelleria.com

Elemento tecnologico	CHIUSURA OPACA INFERIORE
Descrizione	“Per quanto riguarda le tecniche di pavimentazione è di norma eseguito un livellamento della pendenza della roccia su cui poggia il dammuso, con un **vespaio di pietre piatte** che ha anche funzione di isolare dall’igroscopicità della roccia; su questo mosaico di pietre ad incastro poggia con un **battuto di terra rossa** che costituiva la pavimentazione del dammuso. Solo nei dammusi più recenti riscontriamo una pavimentazione di **terracotta maiolicata** e con l’avvento del cemento troviamo spesso un **battuto di cemento**” (Giardina, 2018).

Documentazione fotografica

Figura 38: Pavimentazione interna in terra battuta da www.conoscerepantelleria.it

Figura 39: Pavimentazione interna con piastrelle in terracotta maiolicata da www.pantellerialink.it

Figura 40: Pavimentazione esterna da www.solopantelleria.it

Figura 41: Pavimentazione esterna da www.solopantelleria.it

Elemento tecnologico	CHIUSURE OPACHE E TRASPARENTI VERTICALI (INFISSI E PORTE)
Descrizione	“Tutti gli ingressi ai dammusi sono architravati e l’accesso è posizionato in modo da opporsi ai forti venti dominanti cui l’isola è sottoposta. In tutte le tipologie l’infisso è sempre **arretrato rispetto a filo esterno del muro** (arretrato di almeno 30 cm o posizionato a filo interno del muro)**.** Le pareti dell’ingresso presentano uno sguincio, caratteristica di quasi tutti i dammusi. La chiusura superiore delle aperture poteva essere ad arco, con piattabanda o architrave. Le aperture del dammuso consistono in un **vano di ingresso** e una **piccola finestra** localizzata o nel prospetto laterale o di fronte all’ingresso, di solito orientati verso sud. L’infisso a chiusura delle aperture era molto scarno ed essenziale, generalmente ad un’anta, costituito da **un telaio ligneo** formato da un montante verticale e da traverse orizzontali. Sul telaio venivano inchiodate delle tavole generalmente larghe 10-15 cm. Uno dei sistemi tradizionali di schermatura prevede la presenza di un’anta scusa posta sul lato interno del vetro” (Giardina, 2018).
Dimensioni	Dimensioni pietra architrave: 14x38x30 cm Dimensioni finestre: 40 cmx50 cm Altezza soglia aperture: 180 cm

Vincoli normativi

Piano Territoriale Paesistico dell’isola di Pantelleria Norme di Attuazione, Decreto 26.07.2000

CONSENTITO
Tipologia di infissi: gli infissi devono essere in legno.
Posizionamento infissi: gli infissi devono essere arretrati dal filo facciata.

NON CONSENTITO
Alterazione dei prospetti: non è consentito alterare i prospetti con infissi in alluminio, avvolgibili e zoccolature. Non è consentito bordare di bianco le porte e le finestre dei prospetti in pietra a faccia vista.

Piano Regolatore Generale del Comune di Pantelleria, Norme Tecniche di Attuazione, integrate al 16.09.2014, Capitolo II, art.4 - art. 5

CONSENTITO
Caratteristiche dimensionali degli infissi: le finestre per le nuove costruzioni potranno avere una superficie non inferiore ad 1/12 della superficie calpestabile, il tutto per adeguarli il più possibile al tipico “Dammuso Pantesco”. Per i dammusi esistenti da recuperare senza necessità di demolizione e ricostruzione le finestre potranno avere una superficie non inferiore ad 1/16 della superficie calpestabile e di forma quadrata.

Documentazione fotografica

Figura 42: Infissi in legno da www.conoscerepantelleria.it e www.solopantelleria.com

Elemento tecnologico	ELEMENTI DI SCHERMATURA ESTERNA
Descrizione	“Gli antichi prospetti caratteristici della zona sud-ovest (Scauri e Rekhale) sono caratterizzati da portici in facciata, oggi non più consentiti. Più di recente è d’uso aggiungere sul terrazzo una copertura realizzata con una **struttura di canne e legno chiamata *cannizzato***” (Scarano, 2007).

Vincoli normativi

Piano Territoriale Paesistico dell’isola di Pantelleria Norme di Attuazione, Decreto 26.07.2000

CONSENTITO

Realizzazione di nuovi spazi aperti: possono essere realizzati modesti spazi aperti a monte della casa anche ampliando l'intercapedine esistente purché si crei uno spazio coperto di collegamento tra casa e terreno**.**

NON CONSENTITO

Alterazioni degli spazi aperti: non è consentito chiudere con strutture anche precarie "giardini", arcate di portici o patii.

Documentazione fotografica

Figura 43: Dammuso a Scauri con arcate da www.dammusoarchi.com

Figura 44: Dammuso a Rekhale con arcate da www.abitarepantelleria.it

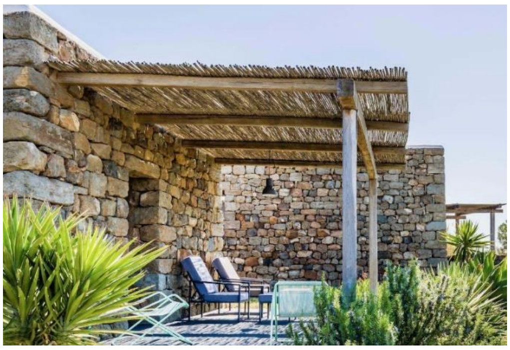
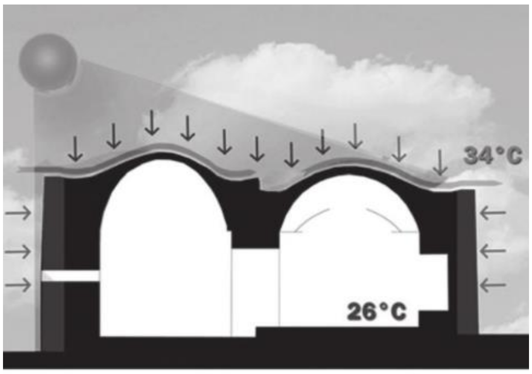


Figura 45: Cannizzato da www.abitarepantelleria.it

Figura 46: Cannizzato da www.abitarepantelleria.it

Elemento tecnologico	DOTAZIONI IMPIANTISTICHE
Descrizione	**Dammuso tradizionale non ristrutturato** "Il funzionamento climatico della costruzione è accentuato ed è duplice. Nella **fase diurna** l'ambiente interno è protetto dall'ingresso della radiazione solare. L'elevata massa muraria consente di attenuare e sfasare l'onda termica e la copertura, di spessore ridotto ma di colorazione chiara, riflette consistente parte della radiazione solare incidente. Attraverso le aperture ridotte si ha l'ingesso di aria e di luce naturale.  *Figura 47: Schema del funzionamento ambientale estivo del dammuso da* Radi (2010) Nella **fase notturna** lo spessore ridotto della copertura e la sua forma a cupola ribassata contribuiscono all'eliminazione del calore accumulato dalla struttura durante il giorno, grazie all'effetto radiativo per via della notevole superficie di scambio verso il cielo. Inoltre, la ventilazione notturna permessa dalle piccole aperture nei muri, dissipa parte del calore accumulato" (Radi, 2010). **Dammuso residenziale ristrutturato** "Per quanto riguarda Pantelleria, i dati contenuti nel "15° censimento generale della popolazione e delle abitazioni" indicano che delle circa 3.300 abitazioni occupate da residenti solo il 5% dispone di un impianto di riscaldamento vero e proprio a servizio dell'intera abitazione, mentre circa il 20% delle abitazioni occupate dispone di apparecchi singoli fissi che riscaldano l'intera abitazione o, con maggior frequenza, solo alcune parti di essa. Prevale quindi la situazione, come detto in precedenza, di eventuale impiego di apparecchi singoli mobili (si utilizzano quasi esclusivamente stufe elettriche). Il vettore energetico di gran lunga prevalente per il riscaldamento degli ambienti è l'energia elettrica (quote minoritarie possono derivare dall'impiego di gasolio o di biomassa). L'energia elettrica soddisfa gran parte dei fabbisogni energetici del settore, compresi quelli per climatizzazione ambienti (riscaldamento e/o raffrescamento), fatta eccezione per gli usi cucina per i quali si fa ricorso al GPL in bombole e che assorbono attualmente la parte rimanente dei consumi energetici di settore. Tra gli usi finali, è senza dubbio la produzione di acqua calda sanitaria a prevalere nettamente in quanto a consumi; gli scaldabagni elettrici si stima arrivino ad assorbire annualmente circa il 30% del consumo elettrico complessivo. Relativamente al condizionamento estivo, questo non risulta pesare in maniera significativa sul bilancio elettrico sul comparto residenziale" (PAES, 2015).

Vincoli normativi

<u>Piano Territoriale Paesistico dell'isola di Pantelleria Norme di Attuazione, Decreto 26.07.2000</u>

NON CONSENTITO

Installazione di impianti solari sulle coperture: sul tetto degli edifici esistenti e delle nuove costruzioni non sono ammessi pannelli solari o fotovoltaici.

Azioni di intevento

<u>Piano d'Azione per l'Energia Sostenibile del Comune di Pantelleria, Gennaio 2015</u>

PROPOSTE DI AZIONE

Introduzione di impianti solari termici e pompe di calore (COP>3) accoppiate a un serbatoio di accumulo per la produzione di ACS in caso di nuova costruzione o ristrutturazione dell'impianto termico.

Gli obiettivi di Piano prevedono che gli impianti solari termici siano installati in modo distribuito sul territorio, vale a dire sui tetti delle abitazioni dove l'acqua calda deve essere fornita o, in caso di tetti "inviolabili" (dammusi), a terra; l'installazione a terra non comporta un notevole impatto visivo, data la superficie contenuta richiesta per gli impianti.

CRITICITA'

Esiste una parte di edifici ove gli interventi non sono tecnicamente possibili (in particolare ciò si riferisce agli edifici sotto tutela architettonica o in particolari situazioni tecnicamente non risolvibili).

Documentazione fotografica

Figura 48: Dammuso residenziale con dotazioni impiantistiche da www.abitarepantelleria.it

Figura 49: Dammuso residenziale con dotazioni impiantistiche da www.abitarepantelleria.it

Figura 50: Inserimento diffuso di un impianto FER a terra da Modernini et al. (2019)

Figura 51: Inserimento diffuso di un impianto FER integrato con una tettoia da Modernini et al. (2019)

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