WIT Transactions on

Ecology and the Environment

VOLUME 262, 2024

WIT PRESS

Sustainable Development and Planning 2024

Sustainable Development and Planning XIII

WIT*PRESS*

WIT Press publishes leading books in Science and Technology.
Visit our website for the current list of titles.
www.witpress.com

WIT*eLibrary*

Home of the Transactions of the Wessex Institute.
Papers contained in this volume are archived in the WIT eLibrary in volume 262 of WIT Transactions on Ecology and the Environment (ISSN 1743-3541).
The WIT eLibrary provides the international scientific community with immediate and permanent access to individual papers presented at WIT conferences.
Visit the WIT eLibrary at www.witpress.com.

THIRTEENTH INTERNATIONAL CONFERENCE ON SUSTAINABLE DEVELOPMENT AND PLANNING

Sustainable Development and Planning 2024

Conference Chairman

Stavros Syngellakis
Wessex Institute, UK
Member of WIT Board of Directors

International Scientific Advisory Committee

Socrates Basbas
Colin Booth
Carlos Borrego
Roman Brandtweiner
Paul Carrion Mero
Maria da Conceicao Cunha
Luca D'Acierno
Siyabulela Fobosi
Eric Gielen
Emanuele Giorgi
Dima Legeyda
Danila Longo
Isabel Madaleno
Robert Mahler
Irina Malkina-Pykh
Jose Luis Miralles i Garcia
Özlem Özçevik
Marilena Papageorgiou
Filomena Pietrapertosa
Dimitris Prokopiou
Elena Rada
Marco Ragazzi
Francesco Russo
Monica Salvia
Marco Schiavon
Marichela Sepe
Carlo Trozzi
Sirma Turgut

Organised by
Wessex Institute, UK

Sponsored by
WIT Transactions on Ecology and the Environment

WIT Transactions

Wessex Institute
Ashurst Lodge, Ashurst
Southampton SO40 7AA, UK

We would like to express our thanks to the conference Chairs and members of the International Scientific Advisory Committees for their efforts during the 2024 conference season.

Conference Chairs

Alexander Cheng
University of Mississippi, USA
(Member of WIT Board of Directors)

Stavros Syngellakis
Wessex Institute, UK
(Member of WIT Board of Directors)

International Scientific Advisory Committee Members 2024

Socrates Basbas Aristotle University of Thessaloniki, Greece
João Batista de Paiva University of São Paulo, Brasil
Alma Bojórquez-Vargas Universidad Autonoma De San Luis Potosi, Mexico
Colin Booth University of the West of England, UK
Carlos Borrego University of Aveiro, Portugal
Roman Brandtweiner Vienna Universiy of Economics and Business, Austria
André Buchau University of Stuttgart, Germany
Paúl Carrión Mero Higher Polytechnic School of the Litoral, Ecuador
João Manuel Carvalho University of Lisbon, Portugal
Weiqiu Chen Zhejiang University, China
Jeng-Tzong Chen National Taiwan Ocean University, Taiwan
Mario Cvetković University of Split, Croatia
Maria da Conceição Cunha University of Coimbra, Portugal
Luca D'Acierno University of Naples Federico II, Italy
Pablo Díaz Rodríguez University of La Laguna, Spain
Eleni Didaskalou University of Piraeus, Greece
Petia Dineva Bulgarian Academy of Sciences, Bulgaria
Eduardo Divo Embry-Riddle Aeronautical University, USA
Hrvoje Dodig University of Split, Croatia
Chunying Dong Beijing Insitute of Technology, China
Mauro Dujmović Juraj Dobrila University of Pula, Croatia
Ney Dumont Pontifical Catholic University of Rio de Janeiro, Brazil
Siyabulela Fobosi University of Fort Hare, South Africa
Zhuo Jia Fu Hohai University, China
Alexander Galybin Schmidt Institute of Physics of the Earth, Russia
Xiao-Wei Gao Dalian University of Technology, China
Eric Gielen Universitat Politècnica de València, Spain
Emanuele Giorgi Tecnologico de Monterrey, Mexico
Luis Godinho University of Coimbra, Portugal
Andreas Karageorghis University of Cyprus, Cyprus
Alain Kassab University of Central Florida, USA
Hiroshi Kato Hokkaido University, Japan
John Katsikadelis National Technical University of Athens, Greece
Dima Legeyda, Newcastle University, UK
Edson Leonel University of São Paulo, Brazil
Daniel Lesnic University of Leeds, UK
Danila Longo University of Bologna, Italy
Isabel Madaleno University of Lisbon, Portugal
Robert Mahler University of Idaho, USA
Irina Malkina-Pykh St Petersburg State Institute of Psychology and Social Work, Russia
George Manolis Aristotle University of Thessaloniki, Greece
Ilia Marchevsky Bauman Moscow State Technical University, Russia
Liviu Marin University of Bucharest, Romania
José Luis Miralles i Garcia Polytechnic University of Valencia, Spain
Juraj Mužík University of Žilina, Slovakia
Yasuo Ohe Tokyo University of Agriculture, Japan
Özlem Özçevik Istanbul Technical University, Turkey
Leandro Palermo Jr State University of Campinas, Brazil
Ernian Pan National Yang Ming Chiao Tung University, Taiwan
Marilena Papageorgiou Aristotle University of Thessaloniki, Greece
Marko Perić University of Rijeka, Croatia
Filomena Pietrapertosa National Research Council of Italy, Italy

This page intentionally left blank

Sustainable Development and Planning XIII

Editor

Stavros Syngellakis
Wessex Institute, UK
Member of WIT Board of Directors

WIT*PRESS* **Southampton, Boston**

Editor:

Stavros Syngellakis
Wessex Institute,UK
Member of WIT Board of Directors

Published by

WIT Press
Ashurst Lodge, Ashurst, Southampton, SO40 7AA, UK
Tel: 44 (0) 238 029 3223; Fax: 44 (0) 238 029 2853
E-Mail: witpress@witpress.com
http://www.witpress.com

For USA, Canada and Mexico

Computational Mechanics International Inc
25 Bridge Street, Billerica, MA 01821, USA
Tel: 978 667 5841; Fax: 978 667 7582
E-Mail: infousa@witpress.com
http://www.witpress.com

British Library Cataloguing-in-Publication Data

A Catalogue record for this book is available
from the British Library

ISBN: 978-1-78466-489-3
eISBN: 978-1-78466-490-9
ISSN: 1746-448X (print)
ISSN: 1743-3541 (on-line)

The texts of the papers in this volume were set individually by the authors or under their supervision. Only minor corrections to the text may have been carried out by the publisher.

Preface

This volume contains edited papers presented at the 13th International Conference on Sustainable Development and Planning, organised by the Wessex Institute of Technology (WIT). This event took place in Seville, Spain from 23 to 25 September 2024.

The contributors to this volume addressed problems related to development and planning, affecting urban and rural areas, and encountered in many regions of the world. Accelerated urbanisation has resulted in the deterioration of the cities' environment and loss of quality of life. Developing new methodologies for monitoring current conditions as well as planning and implementation of novel mitigating strategies can offer solutions towards reducing pollution and the non-sustainable use of available resources.

Energy-saving and eco-friendly building designs have become an important part of modern development, which places special emphasis on increasing efficiency and reducing emissions. Planning has a key role to play in ensuring that such approaches, as well as new materials and processes, are implemented in the most effective manner.

Sustainability in the built environment is a broad area of study covered extensively in this volume with articles dealing with urban planning and design, shared and green spaces as well as sustainable building practices. The impacts on the environment are examined in the contexts of tourism, air pollution and greenhouse gas emissions, diesel to electric mobility transition as well as energy, sugar and bicycle helmet production.

Management strategies for wetlands and national forests, drought, water scarcity and desalination, seawater intrusion are some of the issues discussed under natural resources management.

Public views, the stock market as well as multidisciplinary dimensions and elements of green logistics are explored as the basis for possible sustainable development indicators. The analytic hierarchy process is applied to bridge the gap between aquavoltaics policy planning and stakeholder expectations. It is suggested that expressway construction has a moderating effect on environmental governance and sustained environmental, social and governance performance has an influence on corporate financial performance; also, that the sanctioning process in mining legislation can be strengthened by stakeholders' engagement.

The volume also includes plenty of informative and topical material in the areas of sustainable mobility, energy efficiency, community and city planning, rural areas development, waste management, quality of life as well as the carbon and ecological footprint.

Two special sessions were held at the conference. The subject matter of the first was strategies for environmental sustainability with focus on waste collection, treatment and disposal as well as environmental performance and practices in higher education institutions, in particular. The second special session was dedicated to energy-climate transition through transnational municipal cooperation. Papers from this session deal with adaptation planning for addressing climate change in urban environments as well as local and national authorities' strategies for clean energy transition.

These papers, like others presented at WIT conferences, are uploaded to CrossRef and appear regularly in suitable reviews, publications and databases, including referencing and abstracting services. They are also archived on-line in the WIT eLibrary (http://www.witpress.com/elibrary) where they are permanently available in Open Access format to the international scientific community.

The Editor wishes to thank the members of the International Scientific Advisory Committee who have peer-reviewed the submitted papers. Special thanks go to the Conference Coordinator, Ms Marta Graczyk, WIT's IT Manager, Mr Alan Morgan, and WIT Press Production Manager, Helen Hill, for their significant contribution to the success of the conference and the processing of papers for publication in these Transactions.

Stavros Syngellakis

The Editor, 2024

Contents

Section 1: Sustainable development indicators, governance and policies

Section 2: Energy efficiency

Section 3: Sustainability in the built environment

Section 4: Sustainable mobility

Section 5: City and community planning

Section 6: Rural areas development

Section 7: Waste management

Section 8: Natural resources management

Section 9: Environmental impacts

Section 10: Quality of life

Section 11: Carbon and ecological footprint

Section 12: Energy–Climate transition

Section 13: Strategies for environmental sustainability

ASSESSING ENERGY-SAVING RETROFIT AND CARBON FOOTPRINT REDUCTION OF RURAL DWELLINGS: A CASE STUDY IN TUSCIA, ITALY

CARLO COSTANTINO, STEFANO BIGIOTTI & ALVARO MARUCCI
Department of Agriculture and Forest Sciences (DAFNE), University of Tuscia, Italy

ABSTRACT

In Italy, rural areas represent 60.9% of the national territory, with over 17.0% of the population residing there. Rural buildings across these territories are often historical; therefore, implementing conservative intervention measures to contain energy consumption, produce renewable energy and mitigate environmental impacts is crucial for achieving the climate neutrality goals by 2050. This paper aims to investigate the environmental impacts during a 60-year study period of 12 different thermal insulation solutions applied in the energetic refurbishment of a historical rural dwelling in Valentano, Italy, focusing on the carbon footprint and consumption of primary energy at certain life cycle stages (A1/A3 and C1/C3). The assessment is conducted in two phases: (i) in comparative terms between configurations, adopting the same functional unit (thermal transmittance of 0.193 ± 0.006 W/m^2 K); and (ii) evaluating the intervention applied to the building, considering the avoided impacts in operational energy phase and the overall life cycle impact, cradle-to-grave. This study reveals a correlation between environmental impacts and the mass of material. In particular, the material with the least impact in terms of global warming potential is the flexible wood fibre (8.18 $kgCO_{2eq}/m^2$), while the solution with the overall least impact (considering other necessary materials) is the external thermal insulation composite system using EPS (20.53 $kgCO_{2eq}/m^2$) due to the reduced amount of insulation required. Furthermore, the environmental impact differences between configurations at the building scale are more limited, below 5%, highlighting the significant contribution from the operational phase in the life cycle (about 90%). In light of these results, intervention guidelines using renewable energy sources have been identified and evaluated. In particular, the combined use of heat pump, photovoltaic, and solar thermal systems achieves the zero-energy building standards and reduces emissions by about 80% compared to scenarios focused solely on insulation.

Keywords: rural building heritage, carbon footprint, energy-saving retrofit, zero-energy building, life cycle assessment, regeneration and restoration of rural structures, energy consumption, energy simulations, sustainable architecture, building energy performance.

1 INTRODUCTION

In Italy, 17.00% of the population lives in rural areas, constituting 60.90% of the national territory [1]. To achieve the climate neutrality goals set by the European Commission for 2050, it is necessary to intervene in both urban and rural areas. In urban areas, widespread interventions at the block or district scale can reduce the energy consumption of residential stock. In rural areas, however, interventions are often limited to individual buildings.

In Italy and Europe, rural buildings are constituted mainly of load-bearing masonry structures made of stone or brick. These buildings are often characterised by historical and artistic value but are also inefficient in terms of energy consumption. In this perspective, implementing conservative intervention measures to improve the envelope's energy efficiency, contain energy consumption, produce renewable energy on-site, and mitigate environmental impacts is crucial [2]. In addition, not all insulation systems are always applicable without altering the integrity of the building's appearance, which represents a crucial aspect in order to preserve their cultural and patrimonial value [3]. For this reason, it is essential to investigate the main wall insulation systems.

WIT Transactions on Ecology and the Environment, Vol 262,
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SDP240681

In Italy, external wall insulation accounts for over 70% of interventions, while internal dry-lining insulation represents about 10% [4]. Regarding insulating materials, the market is composed of over 65% polystyrene (EPS or XPS) and 12% mineral fibres (rock wool or glass wool) [4]. These results differ from those of the European market, where the share of mineral materials is much higher, representing over 50% in some cases.

The environmental burdens of insulation materials depend not only on the material and production process but also on many other factors, such as the type of insulation material (blown/expanding/loose material, panel, etc.), the origin of the raw materials, the percentage of recycled material, the distance from the manufacturing site, and the national energy mix [5]. For this reason, to obtain comparable results, it is important to use datasets that employ the same national energy mix and average values for the materials analysed [5].

The environmental impacts of building insulation materials can be separated into two main categories based on their capacity to reduce energy consumption: (i) directly embodied burdens due to their production and installation phases and (ii) avoided impacts due to the reduction in energy consumption [6]. Usually, the operational energy dominates the embodied impacts, especially in the case of existing building renovations [7].

The choice of the functional unit is fundamental in a comparative life cycle assessment (LCA) study to ensure equivalent performances and the correct evaluation of environmental impacts. In comparing insulating materials, some studies use the minimum value to meet national regulations for the thermal transmittance of walls in dwellings [8]. Other studies, however, use a functional unit that relates the thermal parameters of the materials. For example, Grazieschi et al. [6] use $FU = R\ \lambda\ \rho\ A$ in their research, where R is the thermal resistance, λ is the thermal conductivity, ρ is the density, and A is the area equal to 1 m^2. However, it is important to note that even using a correct functional unit, it is difficult to achieve equivalence in all material characteristics, both in terms of performance, such as thermal inertia or fire resistance, and durability, as natural materials are generally less durable.

In recent years, many studies have been conducted on insulating materials to help evaluate solutions for improving the energy performance of building envelopes. Some studies compare insulating materials applied to residential buildings, focusing on the carbon footprint and consumption of non-renewable primary energy (PE-NRe) over a 50-year study period [9]. Other researchers apply LCA to rural buildings with high energy consumption [10]. Still, other papers compare construction systems, evaluating entire external walls to determine which system is more efficient for new constructions [11]. The aim of this research includes:

- To provide meaningful results that can support the choice of insulating material during the initial stages to evaluate the impacts during the life cycle.
- The application of this methodology to evaluate the impacts at the building scale, using a case study representative of the Italian rural building stock.
- Identify and evaluate the life cycle impacts of potential interventions on systems in order to achieve the zero-energy building (ZEB) standard.

2 METHODOLOGY

2.1 Aim and scope of the study

Nowadays, a wide range of technical alternatives exist for insulating the vertical elements of the building envelope. The choice is influenced by factors other than environmental impacts, such as construction cost, speed of installation, and the typology of finishing elements. This article focuses on a representative sample of 12 configurations of wall insulation systems, with six installed inside the wall and six on the outside, in order to determine which configuration results in the least environmental impact. Specifically, for each of the six configurations, whether internal or external, two synthetic materials (EPS and PIR), two mineral materials (rock wool and glass wool), and two natural materials (wood fibre and cork) were selected. This paper is structured into three phases:

- In the first phase, the types of wall insulation systems were individually analysed to evaluate the environmental impacts per square meter of surface area.
- In the second part, these solutions were applied to the case study to evaluate their contribution to overall environmental impacts, excluding the rest of the construction elements as constants.
- In the last phase, in light of the results of these analyses, the best-case scenario is utilised to propose potential intervention guidelines for rural dwellings, encompassing both the building envelope and systems aimed at achieving the ZEB standard.

To assess the impacts associated with the construction process, the analyses include stages related to production (A1–A3), transportation (A4), construction (A5), and end-of-life (C1–C4), as described in Section 2.4.2. The results are presented in terms of global warming potential (GWP) and primary energy (PE) for brevity, although calculations have also been conducted for other environmental indicators.

2.2 Definition of energy-saving retrofit scenarios

The thicknesses of the insulation materials vary in each scenario to achieve a comparable thermal transmittance, set at $U = 0.193 \pm 0.006$ W/m^2 K. The other thermal parameters of the walls are consequently calculated and expressed as periodic thermal transmittance (Yie) and periodic internal area heat capacity (k1). The wall insulation systems have been classified into two main groups:

- Exterior wall insulation systems are identified by the letter (E), while the number indicates the insulating material employed. In all scenarios (Table 1), the external thermal insulation composite system (ETICS) has been utilised, consisting of adhesive and mechanical fasteners ($\lambda = 0.90$ W/m K; $\rho = 1\ 800$ kg/m^3), a thermal insulation panel (thermal parameters are reported in Table 1), fibreglass reinforcement mesh, and finishing plaster ($\lambda = 0.30$ W/m K; $\rho = 1\ 300$ kg/m^3).
- Interior wall insulation systems are identified by the letter (I), while the number indicates the insulating material employed. For all scenarios (Table 2), a dry system has been chosen with the finishes constituted by two panels, each 12.5 mm thick, one made of plasterboard ($\lambda = 0.21$ W/m K; $\rho = 700$ kg/m3) and the other of gypsum fibre board ($\lambda = 0.32$ W/m K; $\rho = 1\ 100$ kg/m3). In the scenarios that employ synthetic materials (I1 and I2) and cork (I6), the panels are directly attached to the existing wall; in the scenarios with mineral materials (I3 and I4) and wood fibre (I5), flexible insulation panels are installed within a dry steel substructure.

2.3 Application to the case study

In the second phase of the study, wall insulation systems are evaluated at the building scale (Fig. 1) to assess the overall environmental impact. In this perspective, a rural dwelling

Table 1: Comparison of thermal parameters of different exterior wall insulation systems.

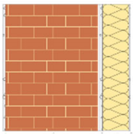	Thermal parameters of materials			Thermal parameters of walls		
	Thickness (m)	Conductivity (W/m K)	Density (kg/m^3)	U-value (W/m^{2}K)	Yie (W/m^{2}K)	k1 (kJ/m^{2}K)
E1: EPS	0.140	0.031	15	0.196	0.002	74.079
E2: PIR	0.120	0.026	35	0.193	0.002	74.073
E3: Rock wool	0.160	0.036	110	0.199	0.002	74.067
E4: Glass wool	0.160	0.034	55	0.189	0.002	74.070
E5: Wood fibre	0.180	0.039	120	0.193	0.001	74.080
E6: Cork	0.180	0.039	120	0.193	0.001	74.074

Table 2: Comparison of thermal parameters of different interior wall insulation systems.

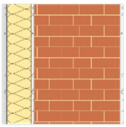	Thermal parameters of materials			Thermal parameters of walls		
	Thickness (m)	Conductivity (W/m K)	Density (kg/m^3)	U-value (W/m^{2}K)	Yie (W/m^{2}K)	k1 (kJ/m^{2}K)
I1: EPS	0.140	0.031	15	0.194	0.003	24.124
I2: PIR	0.100	0.022	35	0.193	0.003	24.598
I3: Rock wool	0.160	0.034	70	0.187	0.003	26.000
I4: Glass wool	0.140	0.031	50	0.197	0.003	24.714
I5: Wood fibre	0.160	0.036	60	0.197	0.003	27.211
I6: Cork	0.180	0.039	120	0.190	0.002	28.199

Figure 1: Photographs and energy model of the case study.

located in Valentano, in the province of Viterbo, within climatic zone E (2101 ≤ HDD ≤ 3000), is used as a case study. This residential building has two floors and a total net area of 180.40 m^2. Table 3 summarises the building's other geometric characteristics.

From a construction point of view, the construction has a load-bearing stone masonry structure with a thickness varying between 50 cm and 60 cm. A wooden insulated roof is present with a thermal transmittance of U = 0.18 W/m^{2}K. The foundation floor is made of insulated reinforced concrete slab (U = 0.26 W/m^{2}K). The rural building presents heating and domestic hot water (DHW) systems, consisting of a condensing natural gas boiler and a cooling system comprising a direct expansion heat pump.

Table 3: Main geometric and building characteristics of the case study.

Gross volume	833.90	No. of residential storeys	2
Gross floor area	585.90	Wall surface internal	220.50
Residential net floor area	180.40	Wall surface external	308.50
Height	7.80	Roof surface	113.50
S/V ratio	0.70	Window surface	23.60

Table 4 details the building's energy consumption. This table includes both the current energy consumption and the consumption following the application of thermal insulation to the building's envelope. In the latter case, no assumptions have been made about the systems, which remain the same as those in the baseline.

Table 4: Comparison of energy consumption in each scenario.

	Heating energy demand (kWh/m^2)	Cooling energy demand (kWh/m^2)	Total PE demand (kWh/m^2 y)	Natural gas consumption (Sm^3/y)	Electricity consumption (kWh/y)
S0: Baseline	181.41	1.06	285.33	5 164	752
E1: EPS	66.39	2.48	116.20	1 919	388
E2: PIR	65.46	2.47	114.81	1 916	389
E3: Rock wool	67.21	2.49	117.44	1 919	387
E4: Glass wool	66.32	2.52	116.15	1 897	386
E5: Wood fibre	63.57	2.85	112.39	1 810	390
E6: Cork	63.57	2.85	112.39	1 810	390
I1: EPS	64.85	2.65	114.10	1 866	389
I2: PIR	63.62	2.62	112.20	1 875	391
I3: Rock wool	64.79	2.69	114.06	1 845	387
I4: Glass wool	63.83	2.76	112.67	1 841	391
I5: Wood fibre	63.76	2.83	112.65	1 820	391
I6: Cork	63.81	2.87	112.78	1 802	389

2.4 Life cycle assessment

2.4.1 The functional units

In the first part of the study, the functional unit was the square metre of external stone masonry wall insulated to ensure a thermal transmittance of $U = 0.193 \pm 0.006$ W/m^{2}K. The non-insulating materials for each scenario were assumed as described in Section 2.2.

In the second phase of the analysis, the different thermal insulation solutions were applied to the case study, covering a total internal vertical surface area of 220.50 m^2 or an external surface area of 308.50 m^2, without making further modifications to the other envelope elements, which were already assumed to be insulated as described in Section 2.2. In this case, the comparison is conducted using the gross internal floor area as the functional unit, which includes the projection of the walls on the floor plan.

2.4.2 Life stage boundary and impact categories

In the first phase of the article, the life cycle of the materials installed in each scenario was analysed, including the following stages: the production of construction materials (A1–A3), transportation and on-site construction (A4–A5), and the disposal phases (C2–C4). The results are expressed in terms of total PE (the sum of non-renewable and renewable PE) and GWP. In this phase, the maintenance and replacement of materials (B1–B5) are excluded from the analysis.

The second analysis phase included all the stages of the first part with the addition of stages B1–B5. A 60-year evaluation period is employed, assuming a complete replacement of the insulating materials after 30 years and of internal/external paints every 10 years. The energy consumption of each scenario (B6) is evaluated to assess the overall impacts of the interventions at the building scale. All stages related to the service life of other building components (B1–B5), the impacts related to operational water (B7), and all phases concerning existing materials, such as roofs, stone walls, and internal partitions, are excluded from the analysis. This decision is based on the fact that some materials are the same in all scenarios, and others, such as stone walls, were produced using traditional techniques, which did not significantly affect the environmental assessment and decision-making process of the insulation system in the initial design phase. Finally, materials constituting furniture, systems, and those located outside the buildings are excluded from the evaluation.

The third part of the study concerning intervention guidelines includes materials added in the various scenarios, such as photovoltaic panels, heat pumps, etc.

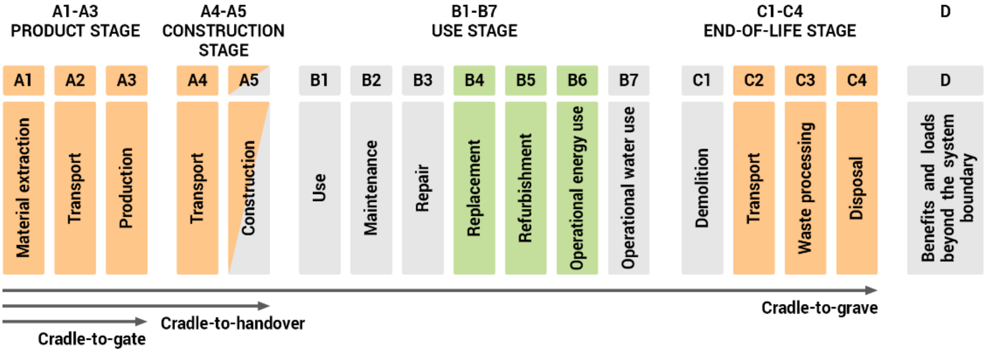

Figure 2: LCA stages assessed in the study: phases considered are in orange; phases analysed only at the building scale are in green.

2.4.3 Source of data and assumptions

The study was conducted in accordance with the standard EN 15978:2011 [12], following the phases outlined in the previous subsection. The analysis was carried out using the software OneClick LCA, employing values of generic materials from the OneClick LCA database that incorporates processes from ECOINVENT. The environmental impact profiles associated with these materials represent median data compatible with the study's objectives, useful in the preliminary stages of the project and indicative of choices regarding insulation materials in accordance with environmental and energy regulations. Regarding the energy mix used in the study's second phase, data specific to the Italian context contained within the same database were employed.

2.4.4 Life Cycle Inventory (LCI)

Production stage (A1–A3): The quantification of materials required for each square metre of external wall was conducted using the OneClick LCA database, which includes data on input and output flows of energy and materials. This encompasses resource extraction, transportation of raw materials to the production site, processing in the factory, and the treatment of generated residues. Table 5 shows the environmental profile characterisation, in terms of GWP and PE-NRe, of the materials analysed in each external wall solution. In accordance with the standard EN 15978:2011 [12], the biogenic carbon absorbed by natural materials was not assessed, taking into account its return to the atmosphere during the end-of-life phase.

Table 5: Environmental profile of materials used per square meter of external wall.

Material	Scenario	Unit	Waste (A5) (%)	GWP (A1–A3) ($kgCO_{2eq}/u$)	PE-NRe (A1–A3) (MJ/u)
ETICS glueing and coating silicate dispersion plaster	Ex	m^2	10.0	5.36	81.46
Outdoor paint, acrylic-siloxane-based	Ex	m^2	10.0	1.27	20.34
EPS graphite insulation panels, 15 kg/m^3, thickness 16cm	E1, I1	m^2	4.0	8.01	170.51
PIR insulation panels, 34.8 kg/m^3, thickness 12cm	E2	m^2	4.0	12.12	287.49
Rock wool insulation panels, unfaced, 100 kg/m^3, thickness 16cm	E3	m^2	8.0	21.92	304.85
Glass wool insulation in batts unfaced, 65 kg/m^3, thickness 16cm	E4	m^2	8.0	29.43	413.63
Wood fibre insulation panels, 180 kg/m^3, thickness 18cm, 21.6 kg	E5	kg	8.0	16.92	270.22
Expanded insulation corkboard, 115 kg/m^3, thickness 18cm, 21.6 kg	E6, I6	kg	8.0	16.42	210.20
Plasterboard, 10% rec. gypsum, 858 kg/m^3	Ix	m^2	12.5	2.99	31.53
Polypropylene vapor barrier, 0.18 kg/m^2	I1, I3, I4, I5, I6	m^2	10.0	0.71	20.36
Fiber-gypsum board, 1200 kg/m^3	Ix	m^2	12.5	3.12	40.98
Indoor paint	Ix	m^2	10.0	1.26	20.22
Steel profiles, 60% recycled, 3.2 kg	I3, I4, I5	kg	3.3	6.85	110.71
Polyurethane panel, aluminium double-faced, 35 kg/m^3, thickness 10cm	I2	m^2	4.0	9.75	240.06
Rock wool insulation panel, unfaced, 70 kg/m^3, thickness 16cm	I3	m^2	8.0	15.12	208.36
Glass wool insulation panel, unfaced, 50 kg/m^3, thickness 14cm	I4	m^2	8.0	8.01	132.53
Wood fibre flexible insulation, 50 kg/m^3, thickness 16cm, 9.6 kg	I5	kg	8.0	7.47	115.01

Transportation phase (A4): The quantification of transports from production facilities to the construction site was calculated using the following literature values: 100 km for massive materials [13] and 150 km for others. In addition, it was assumed that the materials are transported via diesel-powered trucks with a capacity of 40 tonnes and a 100% fill rate (0.0383 $kgCO_{2eq}$/ton km).

Construction stage (A5): The quantification of impacts resulting from construction site operations depends significantly on the machinery used, typically amounting to about 4%–5% of the building total (A1–A3) [14]. Operations for installing insulation material are the same in all scenarios and are conducted primarily using manual electric tools with very limited impacts. For these reasons, these operations are not considered in the analysis. Stage A5 is evaluated only as follows: (i) the percentage of material lost as waste during construction, assessed according to OneClick LCA process assumptions, typically between 4 and 8% for insulation materials; and (ii) the removal of old plaster and paints (interior or exterior depending on the scenarios) and the corresponding transportation to waste processing and disposal.

Use, maintenance, repair, and replacement stage (B2–B4): These stages encompass the environmental impacts of materials used for maintenance, repair, and replacement operations during the study period, including the corresponding waste flows. These stages were evaluated only in the second part of the research, estimating that paints are completely replaced every ten years and insulation materials with related finishes every 30 years.

Operational energy stage (B6): This stage evaluates the energy consumption resulting from heating and cooling needs during the service life of the dwelling. This stage was assessed only in the second part of the research, estimating the building's consumption in terms of electricity and natural gas through energy simulation in each scenario. The results of this simulation are summarised in Table 4. The environmental profile resulting from energy consumption was evaluated using data related to the Italian context from the OneClick LCA database: for electricity, according to a study for country-specific electricity mixes based on IEA 2022; for natural gas, to the OneClick LCA database of 2023.

Operational water stage (B7): This stage was not evaluated in the analysis as water consumption remains constant across all scenarios, and there are no interventions on the systems to reduce water consumption.

Demolition phase (C1): The environmental impacts resulting from the demolition process of the insulation panels at end-of-life were not considered as they are the same in all scenarios and involve manual operations with reduced impacts.

End-of-life stages (C2–C4): Transportation from the site to disposal (C2) was carried out using specific transportation data depending on the specific process, employing average distance data. Waste treatment and disposal (C3–C4) were estimated using the OneClick LCA database, quantifying the machinery required for processing the weight of materials in each scenario.

3 RESULTS

3.1 Comparison of results from different wall insulation systems

The analysis of the results is presented in two different charts: the first one (Fig. 3, top) illustrates the results in terms of GWP and PE, indicating the contribution of each material required for the insulation intervention; the second one (Fig. 3, bottom) shows the same results but specifies the contribution of each phase. From the first chart, it is evident that the contribution of the insulating material is the most significant compared to other materials considered in each scenario. Specifically, it can be observed that mass significantly impacts overall environmental effects. Despite higher emissions per kilogram of produced material, the lower total quantity of insulating material required to achieve the specified performance makes the E1-EPS scenario the one with the least environmental impact in terms of both GWP and PE. This result is also highlighted by observing the lower environmental impact of internal insulating materials, generally low-density, compared to their external counterparts.

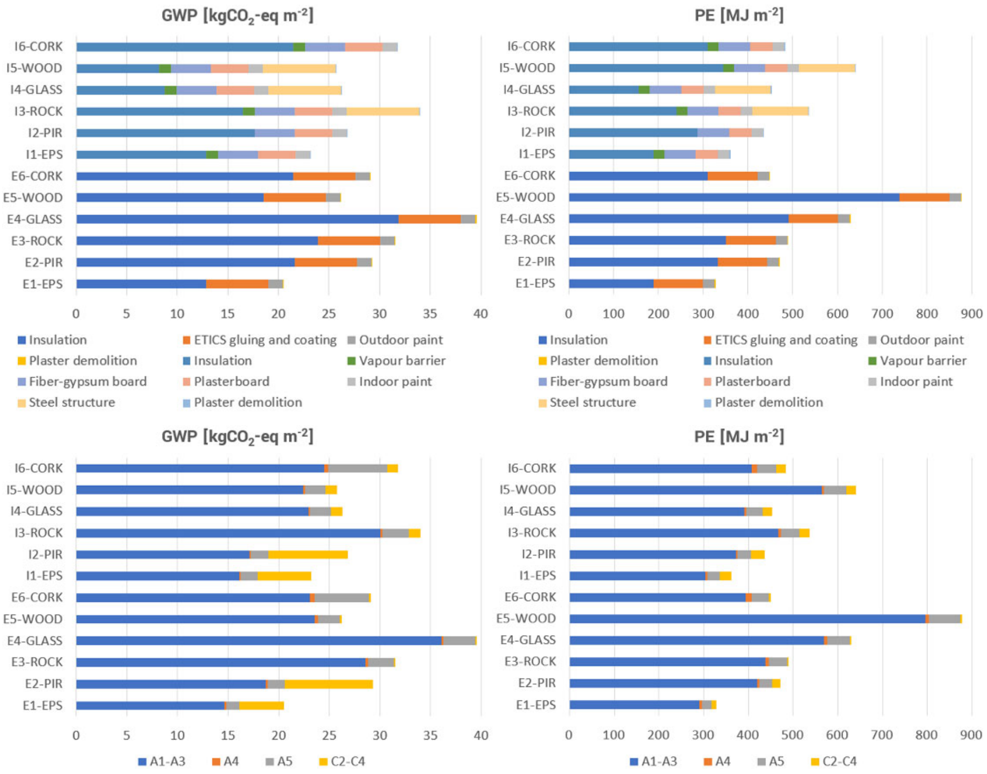

Figure 3: Life cycle impact assessment results in terms of GWP and PE: at the top, divided by each material; at the bottom, broken down by life cycle phases.

3.2 Comparison of results from the application to the case study

At the building scale (Fig. 4, centre), the differences between scenarios are lower. Compared to the initial baseline scenario (S0-Base), the most effective scenarios (I5-Wood and I6-Cork) achieve a GWP reduction of 62.76%, while the worst-case scenario (E4-Glass) achieves 58.41%. The difference between the scenarios is limited in terms of $kgCO_{2eq}/m^2$ (Fig. 4, bottom). Compared to the E1-EPS scenario, the others involving synthetic and mineral materials have higher impacts. All other scenarios have lower impacts.

As expected, the impacts at the building scale are particularly influenced by the operational energy phase: over a 60-year analysis period, the use phase accounts for about 90% of the impacts in all scenarios (Fig. 4, top). The variation in phase B6 between the scenarios is mainly due to the energy required for heating. The energy consumption is minimally influenced by the variation in the thermal transmittance of the external walls between the scenarios ($U = 0.193 \pm 0.006$ W/m^2 K) but is primarily affected by the placement

Figure 4: Results expressed at building-scale: at the top, carbon footprint assessment as a percentage of the E1-EPS scenario; in the middle, comparison with the baseline (no interventions); at the bottom, comparison expressed in terms of $kgCO_{2eq}/m^2$.

of the insulation (internal or external) and the variation in thermal inertia between the solutions. From the energy simulation, scenarios with internal insulation characterised by high density and high heat capacity ensure lower energy consumption, significantly influencing the GWP results.

3.3 Guidelines for energy-saving interventions in rural dwellings

In the final phase of the analysis, the E1-EPS scenario was used as a reference to develop some intervention guidelines at the system level to achieve the ZEB standard. Specifically, four improvement scenarios were considered:

- S2-HP: This scenario involves replacing the thermal system, consisting of a gas boiler and radiators, with a new hydronic heat pump system and fan coil units.
- S3-HP/FV: This scenario includes the interventions of S2-HP and the addition of a 6.0 kW photovoltaic system.
- S4-HP/SL: This scenario includes installing the components from S2-HP and adding a solar thermal system.
- S5-HP/FV/SL: This scenario involves installing all the elements from the previous scenarios.

The results of this simulation were presented in two different charts: the first (Fig. 5, top) illustrates the PE consumption in each scenario for heating, cooling, and DHW; the second (Fig. 5, bottom) compares the GWP and PE, indicating the contribution of each phase. From the charts, it is clear that insulating the building envelope alone is not sufficient to reduce the environmental impacts of dwellings. The second graph shows that replacing the boiler reduces about 40% in GWP and about 35% in PE. The other scenarios, which also include the use of renewable energy sources produced on-site (S3-HP/FV and S4-HP/SL), lead to further significant reductions: approximately 65% and 72% in GWP, and about 64% and 70% in PE, respectively. The scenario that includes all interventions (S5-HP/FV/SL) brings PE-NRe consumption over the 60-year service life to zero. This result drastically reduces the impacts compared to S1-EPS EXT, achieving a reduction of about 80% in both GWP and PE.

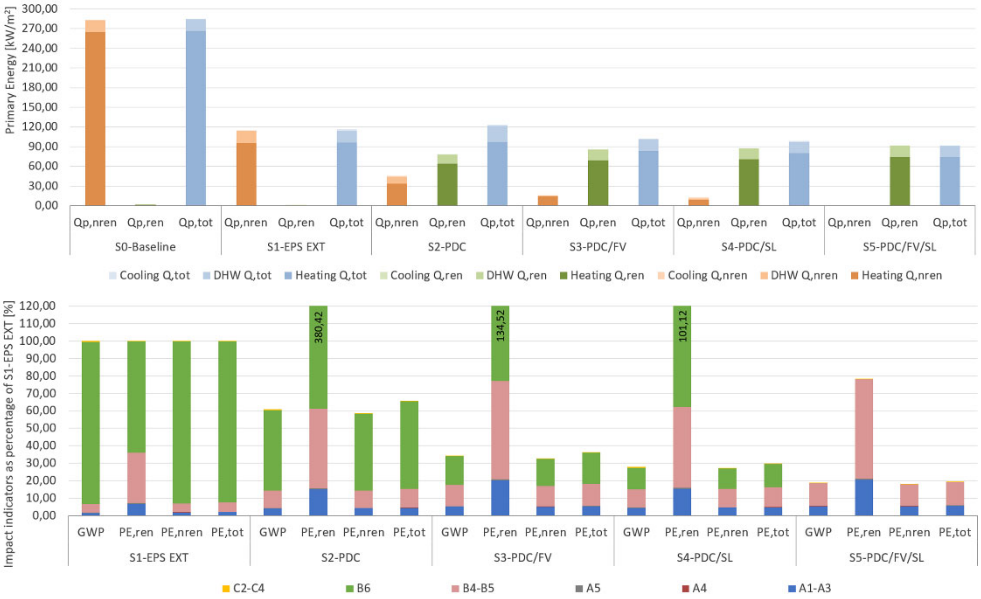

Figure 5: Comparison of recommended intervention scenarios: at the top, expressed as a variation in PE needed for heating, cooling, and DHW; at the bottom, as a variation of total GWP and PE, also considering the impact of materials.

4 CONCLUSIONS

This article investigated some of the main insulation materials used to create thermal insulation solutions in external walls, both exterior and interior, to determine which ones have the least impact on the life cycle in terms of GWP and PE.

This analysis has found no significant difference in impacts between external and internal insulation solutions despite the diversity of materials used for non-insulation purposes. The key factor influencing environmental impact remains the choice of insulation material. In addition, it is possible to identify a correlation between impacts and the mass of material, regardless of the type of insulation. Indeed, it can be observed that the same insulation material in low-density versions has lower impacts. The material with the least impact in terms of GWP is the flexible wood fibre (I5-Wood), while the solution with the overall least impact (considering other necessary materials) is the external with EPS (E1-EPS) due to the reduced amount of insulation required.

At the building scale, analysing life cycle impacts over 60 years shows that the type of insulation material plays a secondary role in the overall assessment, predominantly driven by the operational energy phase. Indeed, this phase is very similar across all scenarios due to the selection of functional units in the initial phase based on thermal transmittance.

In the light of these results, intervention scenarios using renewable sources to reduce energy consumption have been identified and evaluated. It has emerged that all scenarios are highly effective in reducing both energy consumption and emissions. In particular, the combined use of heat pump, photovoltaics, and solar thermal systems eliminates the PE required for heating/cooling/DHW, achieving the ZEB standards and reducing emissions by about 80% compared to scenarios focused solely on insulation.

REFERENCES

[1] National Institute of Statistics (ISTAT), *Territorio*. Istituto Nazionale di Statistica: Rome, Italy, pp. 18–19, 2022.
[2] Cellura, M., Ciulla, G., Guarino, F. & Longo, S., Redesign of a rural building in a heritage site in Italy: Towards the net zero energy target. *Buildings*, **7**, 68. 2017.
[3] Martínez-Molina, A., Tort-Ausina, I., Cho, S. & Vivancos, J.L., Energy efficiency and thermal comfort in historic buildings: A review. *Renewable and Sustainable Energy Reviews*, **61**, pp. 70–85, 2016.
[4] ANIT, Rapporto ANIT 2013: Il Mercato dei Materiali Isolanti in Italia, pp. 13–14, 2014.
[5] Shrestha, S.S., Biswas, K. & Desjarlais, A.O., A protocol for lifetime energy and environmental impact assessment of building insulation materials. *Environmental Impact Assessment Review*, **46**, pp. 25–31, 2014.
[6] Grazieschi, G., Asdrubali, F. & Thomas, G., Embodied energy and carbon of building insulating materials: A critical review. *Cleaner Environmental Systems*, **2**, 100032, 2021.
[7] Biswas, K., Shrestha, S.S., Bhandari, M.S. & Desjarlais, A.O., Insulation materials for commercial buildings in North America: An assessment of lifetime energy and environmental impacts. *Energy and Buildings*, **112**, pp. 256–269, 2016.
[8] Tingley, D.D., Hathway, A. & Davison, B., An environmental impact comparison of external wall insulation types. *Building and Environment*, **85**, pp. 182–189, 2015.
[9] Silvestre, J.D., Castelo, A.M., Silva, J.J., de Brito, J.M. & Pinheiro, M.D., Retrofitting a building's envelope: Sustainability performance of ETICS with ICB or EPS. *Applied Sciences*, **9**(7), 1285, 2019.
[10] Bigiotti, S., Costantino, C. & Marucci, A., Agritourism facilities in the era of the green economy: A combined energy audit and life cycle assessment approach for the sustainable regeneration of rural structures. *Energies*, **17**(5), 1101, 2024.
[11] Mazur, Ł. & Olenchuk, A., Life cycle assessment and building information modeling integrated approach: Carbon footprint of masonry and timber-frame constructions in single-family houses. *Sustainability*, **15**(21), 15486, 2023.
[12] EN 15978, Sustainability of Construction Works: Assessment of Environmental Performance of Buildings – Calculation Method.
[13] Bribián, I.Z., Capilla, A.V. & Usón, A.A., Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment*, **46**(5), pp. 1133–1140, 2011.

[14] Asdrubali, F., Baldassarri, C. & Fthenakis, V., Life cycle analysis in the construction sector: Guiding the optimisation of conventional Italian buildings. *Energy and Buildings*, **64**, pp. 73–89, 2013

Author index