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Exploring the Role of Building Envelope in Reducing Energy Poverty Risk: A Case Study on Italian Social Housing

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Abstract: Energy poverty is a significant social, economic, and health issue which increasingly affects millions of households worldwide. Both climate change and the socio-economic crisis have aggravated this phenomenon, making families unable to keep adequate comfort conditions at home because of economic constraints and/or dwelling inefficiencies. Considering the recent inflation trends, as well as the global effort to reduce the building sector's carbon emissions, energy retrofitting of buildings emerges as the most forward-looking strategy to cope with energy poverty risk. In the case of large building stocks, which are typical for social housing complexes across the EU, deep and fast energy retrofitting might prove challenging, especially considering the resource shortages and disruptions to occupants that may arise. Therefore, this article investigates the relationship between the envelope's insulation ratio and the risk of energy poverty for households. To this end, diverse scenarios are defined, corresponding to progressive increases in the percentage of building envelope that is insulated. The resulting energy needs are calculated for each of them and correlated with local average incomes and relative energy expenses of households. This is tested on an Italian social housing demo case. The results confirm a predictable but not linear correlation between thermal insulation and reduced energy needs for heating, and an interesting side effect on cooling needs for scenarios that perform better in winter. As for income, energy cost has a greater effect on the energy poverty risk when monthly rent is lower, while energy prices have a major role when rent per month is higher.

Keywords: energy poverty; thermal insulation; building energy performance; building envelope; social housing; family income

Citation: Fabbri, K.; Marchi, L.; Antonini, E.; Gaspari, J. Exploring the Role of Building Envelope in Reducing Energy Poverty Risk: A Case Study on Italian Social Housing. *Energies* **2023**, *16*, 8093. https://doi.org/10.3390/en16248093

Academic Editors: Ayman S. Mosallam and Chi-Ming Lai

Received: 20 November 2023
Revised: 7 December 2023
Accepted: 13 December 2023
Published: 15 December 2023

1. Introduction

The recent instability of the energy market, especially across the Western world, due to a combination of reasons within the global scenario, increased the number of people and households struggling with so-called energy poverty. The International Energy Agency estimated that the number of households spending over 10% of their income to cover the expense of energy used in their homes increased by 160 million between 2019 and 2022 [1]. The 10% ratio between family income and money spent on energy is assumed to be the threshold of energy poverty, which is currently a significant social, economic, and health issue affecting a large portion of the population who is forced to choose between meeting their basic health needs and paying the energy bills [2–10].

The COVID-19 pandemic and the energy crisis have contributed to economic depression, thus exacerbating poverty and especially impacting the most vulnerable population groups that had already been in critical situations [11,12]. According to the latest World Energy Outlook (2022), these crises have left more than 75 million people unable to afford basic energy services [1].

This is exacerbated by the fact that the less fortunate citizens—who typically live in low-energy-efficient buildings and use more obsolete, inefficient systems and appliances—have to pay more for operational energy at home. Indeed, the poorest households in developing economies use on average nine times less energy than the wealthiest households, but they spend a much higher percentage of their income on energy services. However, energy poverty is not only an issue in developing countries, but also in the most advanced economies, including Western countries [13]. In the European Union alone, over 30 million citizens (ca. 6.9% of the EU population) were not able to keep homes adequately warm in 2021 [14]. This already worrying situation is expected to worsen fast, as just one year later (2022), this figure reached 9.3% [14]. Therefore, tackling "consumer vulnerability" (often used as a synonym for energy poverty) while ensuring a green transition is a top priority for most countries around the world. In other words, it is becoming a matter of climate justice [15].

Despite the fact that the income–energy cost ratio is used as the main indicator, energy poverty is rather a complex issue, as it can occur "when energy bills represent a high percentage of consumers' income, or when [consumers] must reduce their household's energy consumption to a degree that negatively impacts their health and well-being" [16]. So, before depicting the framework of current research and initiatives in this field, it is worth providing some clarifications on the initial assumptions and definitions of energy poverty.

1.1. Context and Definitions

There is no official definition of energy poverty, and the meaning of the term varies from country to country [17,18] according to the perspective from which the topic is looked at. Accordingly, the phenomenon is also known by different terms such as "fuel poverty", "energy vulnerability", and "energy deprivation". However, everyone agrees that it stems from an imbalance between the economic resources required to meet a household's basic energy needs and family income [11]. Such a disparity could be caused by a variety of factors, ranging from low household income to inefficient buildings and appliances or a combination of the two [19,20], or even other factors like inflation rates. Finally, social norms have also been detected as relevant factors [21].

As anticipated, households typically fall into energy poverty when they spend more than 10% of their income on basic energy services, as stated in the first definition by Brenda Boardmann in 1991 [22,23], but this percentage can vary on a country-by-country basis. In Italy, for example, the Italian Observatory for Energy Poverty (OIPE) points out that the threshold is reached when 6% of the household income is used to pay the energy bill [12]. Lowest-income families, often living in social housing, may pay more for energy bills than for rent [24].

As a possible response, several national authorities ensure discounted, flat, or cap rates directly applied to the energy bills to limit their impact on family income.

At a global level, the 2030 Agenda has designated a specific Sustainable Development Goal for this topic, namely SDG 7—Affordable and Clean Energy [25,26]. This goal is deemed critical because the lack or difficulty of access to energy may prevent economic and human development.

In the European legislative sector, the term energy poverty was first used in the "3rd Energy Package" (Directive 2009/72/EC; Directive 2009/73/EC) where it is stated that "Member States shall take appropriate measures to protect final customers, and shall, in particular, ensure that there are adequate safeguards to protect vulnerable customers. In this context, each Member State shall define the concept of vulnerable customers which may refer to energy poverty and, inter alia, to the prohibition of disconnection of electricity (gas) to such customers in critical times". But it is by the "Clean Energy for All Europeans package" that the need for urgent measures and criteria was strongly highlighted [27], especially in relation to the building Renovation Wave [28]. The Directive 2018/844/EC reports that "the need to alleviate energy poverty should be taken into account, in accordance with criteria defined by the Member States. While outlining national actions that contribute to the alleviation of energy poverty in their renovation strategies, the Member States have the right to establish what they consider to be relevant actions" [29]. Accordingly, several EU countries have integrated targeted measures into their national strategies as part of their obligation to assess energy poverty in their National Energy and Climate Plans (NECPs), and are developing their definitions, measurement and monitoring methods, and solutions to fight energy poverty.

As a consequence, great efforts to provide common indicators and metrics have been made, given that these can influence the ratio and type of population to be addressed by policies [30]. These are generally based on multiple indexes to consider the interrelated factors influencing a such complex issue and cover the diverse possible measures that need implementing [31]. The European Energy Poverty Advisory Hub includes the following: "ability to keep home adequately warm", "arrears on utility bills", "dwelling comfortably cool in summertime", "dwelling comfortably warm in wintertime", "high share of energy expenditure in income" [32].

This suggests that the topic requires investigation considering three major factors: household income and energy costs (economic issue), user comfort and well-being (health issue), and house performance (role of building quality).

1.2. The Economic Issue in Energy Poverty

Family income and the related ability to pay for basic energy services are at the root of energy poverty and the related social and health problems. Indeed, the likelihood of living in uncomfortable and unhealthy conditions (cold/heat stress) rises as low-income people's ability to pay for costs decreases, and the decision to turn off the heating to save money becomes more frequent [33–37]. Health shocks due to discomfort conditions at home are indeed more frequently registered in low-income families [37]. Vulnerable consumers with little money available first pay for rent or mortgage, then buy food, and as a third step, if still possible, pay for utilities [38]. However, inflation rise may affect food prices and mortgage interest as well accelerating the process and reducing the effectiveness of any potential subsidies.

This is what happened, for example, in Italy. As shown by OIPE based on ISTAT data [39], in 2021, energy prices increased by an average of +35% and gas by +41% compared to 2020, strongly impacting consumers' vulnerability. Moreover, the recent national report on energy poverty also clearly illustrates the impact of income. Most affected families live in southern Italian regions, where—despite milder winters and thus lower energy demand for heating—incomes are typically lower and thus the relative cost of basic energy services is higher [40]. For the same reasons, families from inland and/or marginalized areas are proven to be more impacted. Both in southern and northern Italy, significant differences are also recorded between Italian and immigrant families; the latter are, on average, doubly exposed to the risk of falling into energy poverty.

1.3. The Health Issue in Energy Poverty

Energy poverty can negatively affect the comfort, well-being, and health of people, both directly and indirectly, due to the decisions that this condition forces them to take or because of external factors to which they are subjected. In fact, the current understanding of this phenomenon shows that people who live in homes with poorly functioning heating and cooling systems experience significant impacts on their quality of life and lifestyles [31,41–45]. Conditions of high indoor discomfort are usually perceived with temperatures below 16 °C in winter and above 28 °C in summer, especially at night [46,47].

This frequently has an immediate negative impact on health, even affecting the respiratory and cardiovascular systems in the long term. It may also have an impact on mental stability and the person's perception of his/her social identity, which contrasts with the achievement of sustainable development based on a green and just transition [48]. There is also a correlation between low indoor temperatures and mortality [49,50], as well as between childhood asthma and humidity or mold, which are almost always due to hygrothermal imbalances and thermal bridges/local heat loss [51].

Fuel-poverty-related health diseases can arise both in winter and in the summertime. It is in fact demonstrated that severe winters could raise mortality rates [38]. The World Health Organization (WHO) and several academic studies discuss the link between low-income households, the so-called "cold buildings", and related health diseases [52–55]: children (under 4 years old) and elders (over 70 y.o.) are among the most affected age bands. However, in light of the expected rise in global temperatures due to climate change, an increase in the number of deaths from heat waves is also projected for the coming years all over the world [40,56,57].

The cause of these consequences might be either behavior-driven (users setting systems below/above comfort standards to save money), economically driven (users do not have the money to pay pending energy bills) or otherwise (e.g., the building construction and systems features do not allow the indoor spaces to reach the desired temperatures because of inefficiencies).

1.4. The Role of Building Quality in Energy Poverty

Building features strongly impact both operational energy costs and people's well-being, representing a cause of or a significant contributor to falling into energy poverty [5,17,58]. Two main elements are usually involved: heating and cooling systems and building envelopes. In addition, dwelling size and its related energy needs can also impact the ability of a family to afford basic energy expenditures and thus to meet "energy solvency" [59].

This is especially valid for multi-dwelling low-quality housing, where systems are often obsolete or largely inefficient and are the first to be replaced when renovations can be undertaken due to their higher impact and ease of intervention [60]. However, the effectiveness of these interventions can be limited if thermal dispersions from the building envelope are not adequately avoided.

Therefore, over the past few decades, great effort has been made to investigate feasible and affordable solutions to encourage renovations that would allow the existing stock to achieve the required standards [61–63]. Despite the relevance of building envelopes in shaping the energy demand of housing, the literature about its relationship with energy poverty is still limited and only recently has its role been included in official EU documents.

The recurrency of different building types as well as their features and performances vary country by country; however, the TABULA project [64,65] tried, with a certain approximation, to group them into quite well-defined categories (namely single-family houses; multi-family houses; apartment blocks; etc.) to enable more reliable comparative approaches with relation to energy performance. According to the project and literature outcomes, multi-family dwellings emerge as the most critical housing type across the European Union and beyond [66,67], being largely built after the Second World War [68]. Multi-family buildings, and especially those managed by social housing agencies or associations, are structurally affected by several deficits, both functional and technical, which are difficult to solve.

In certain countries, such as Italy, other complexity factors emerge, such as the fragmentation of decisional power, which is usually in the hands of different owners and/or large managing agencies with limited spending capacity [69–71]. This generates the need to consider not delivering interventions in one single step, but instead proceeding with incremental steps involving different parts of the building depending on resource availability and the owners' commitment to proceed.

Overall, at least in Europe, improving building thermal insulation is largely recognized as a way to reduce energy poverty incidence, as described by Neri et al. [72] and Frasca et al. [73]. But still, there is an open challenge to adopt a framework that includes technical, environmental, and economic topics. Among the most promising contributions to this end, Furtado et al. [74] depict a guideline for retrofitting scenarios of EU building stock (as an upgrade of the TABULA project). Its novelty lies in considering the changing climate condition of European countries and the increasing relevance of energy demand for cooling during the summer season. Accordingly, they suggest to include cooling degree days (CDDs), referring to the summer season, in the process, in addition to heating degree days (HDD), which refer to the winter season and are conventionally taken into account. As described by Castano-Rosa et al. [75], the increase in the use of cooling, due to a rapidly changing climate, is largely reshaping energy demand and can heavily impact household expense capacity, which is related to energy poverty risk.

1.5. Energy Poverty in Europe

Aiming at tackling energy poverty further and supporting Member States, the EU has worked on several levels [16], such as addressing energy poverty in the Clean Energy Package [76]. Building on the recommendation of tackling the issue urgently, the "Fit for 55% package" proposed specific measures to identify key drivers of energy poverty risks for consumers, such as excessively high energy prices, low household income, and poor energy efficiency of buildings and appliances, considering structural solutions to vulnerabilities and underlying inequalities [77,78].

The Energy Efficiency Directive [79–81] in Art. 8, "Energy savings obligation", reports that "Member States shall establish and achieve a minimum share of the required amount of cumulative end-use energy savings among people affected by energy poverty, low-income households, vulnerable customers and, where applicable, people living in social housing", with Member States obligated to develop a robust long-term strategy as reported in Art. 22, "Empowering and protecting vulnerable customers and alleviating energy poverty".

Moreover, the Energy Performance of Buildings (recast), adopted by the European Parliament on 14 March 2023 and currently under discussion [82,83], asks each Member State to adopt a national building renovation plan (article 3) including "a roadmap on the reduction of energy poverty and energy savings achieved among vulnerable households and people living in social housing comprising of nationally established targets and an overview of implemented and planned policies and funding measures supporting the elimination of energy poverty". Despite these, Thomson et al. argue that effective measures capable of alleviating fuel poverty in the EU are still lacking or too fragmented across a range of EU Directives [84].

Among EU countries, the United Kingdom—now a former member state—certainly has the most experience in tackling fuel poverty [85]. The UK has been a frontrunner in terms of policies, strategies, and indicators during the past years, especially among northern European countries where cold winters represent an important challenge for national authorities.

Given the recent attention of the European Union to energy poverty [86], several other countries have started research and launched measures to tackle it [87,88], including Portugal [89], Spain [90,91], and Poland [92].

Compared to northern countries, it emerges that slightly different factors are the center of attention in southern European countries, in which climate change also impacts summer weather and which have recently taken serious actions against the potential effects of urban heat islands and heat waves. This is the case in Italy, where cooling degree days are expected to rise significantly [40].

Italy has started tackling energy poverty in 2009 through social tariffs for electricity and gas bills (gas being the primary heating fuel), but still lacks both an official definition and metrics for energy poverty, which would certainly help with the harmonization of monitoring indicators and the development of more effective tools [40,93,94]. In terms of numbers, compared to the 28 EU Member States, in 2020, Italy ranked sixth per number of people unable to adequately heat their houses, but performed better in other indicators, such as the share of the population with arrears on utility bills (21st) [95]. On the national level, the goal of energy poverty reduction is addressed by the Integrated National Energy and Climate Plan 2021–2030 (PNIEC is the Italian acronym), which was submitted to the European Commission in 2019, and is now under revision [96]. A specific section of the PNIEC concerns energy poverty and includes (a) reducing the energy bills of families, (b) improving housing energy efficiency, and (c) providing subsidies to low-income families.

So, in recent years, great effort has been made to provide electricity and gas bonuses, as well as tax reductions for building energy retrofitting, but these have proven not to be effective in alleviating the issue in the long term. The Plan also stresses the relevance of renewable energy communities as a strategy to support energy-poor families.

In 2020, the Italian Energy Poverty Observatory (OIPE) pointed out that the national energy program should be revised to consider energy poverty more seriously [12]; the PNIEC was indeed regarded to focus only on carbon neutrality targets and not to properly consider the social vulnerabilities related to energy poverty [97]. The pandemic has indeed further exacerbated social vulnerabilities in the country by exposing a large portion of the population to increased income uncertainty, wage stagnation, greater permanence in the home—thus raised utility costs—and to a general intensification of psychological and psychic stress.

Although data are dependent on the indicators used for measurement, it is estimated that on average 8.8% of Italian households were energy-poor in 2018 [98]. In 2020, this dropped down to 2.1 million households (8%). However, significant differences at the regional level exist, ranging from 6–10% of frequency in northern Italy to 26–36% in the south [99]. Unfortunately, this decrease only lasted momentarily: in fact, at the end of 2021, about one out of ten Italian households were energy-poor (2.2 million families, corresponding to ca. 8.5% of the national population) [39]. Considering the relevance of the issue, in 2023, ISTAT dedicated for the first time an entire section of the Annual Country Report to energy poverty: the Institute reported that 17.6% of families at risk of poverty are unable to heat their homes [85].

According to this framework, it emerges that the conventional strategy of subsidization alone will not be able to significantly improve the living conditions of poor households in the long term but only mitigate the impact of inflation rates or temporary circumstances, requiring more stable measures to combat the effects of low-quality buildings which represent a structural condition feeding the negative spiral.

Combining the two approaches would certainly be the most desirable option in terms of maximizing the beneficial effects in the short and medium terms. However, this requires huge resources to be invested at the same time; given that energy costs can vary and that their effect on income can be significantly conditioned by inflation rates (with a reduction in residual spending availability), subsidies cannot be reduced while supplementary investments are needed to support renovations, which can sometimes lead to the inhabitants having to move elsewhere during the process, possibly causing additional expenses. Viable options to reduce inefficiency levels in existing buildings with reduced disruption for the end-users still represent an open and urgent field of research. Additionally, a gap in the adequate detection of the poorer sections of the population that risk falling into energy poverty is still a major issue which varies widely depending on the selected indicator.

1.6. Research Aim and Goals

Following these premises, it follows that energy poverty depends on three main drivers: (a) family income and related spending capacity due to inflation trends; (b) energy prices, correlated to the energy market and geopolitical circumstances; (c) dwelling or building energy performance, which is strictly connected to (c.1) building envelopes and (c.2) technical systems, especially those related to heating and cooling.

This study aims to give more emphasis to the role of building envelopes in preventing the risk of energy poverty and to consider the benefit of incremental solutions to mitigate the effect of such issues while distributing the cost of retrofitting interventions instead of focusing on one-off investments or subsidies.

The study reported in this article focuses on the role of building envelopes as an active tool to structurally combat energy poverty risk while reducing energy needs for heating and cooling as well as primary energy needs, thus generating energy bill savings for families.

The primary goal is to investigate how the different parts of a building envelope—corresponding to different percentages of coverage of the insulated surface—influence its thermal and energy performance with a consequent impact on reducing energy poverty risks for households. Compared to other studies, the novelty of this research project lies in focusing on the feasibility of improving envelope thermal insulation, which is usually not primarily considered because of high upfront costs. To this end, this study correlates the percentage of insulated envelope with its effect on energy poverty reduction, and as a result, it addresses retrofitting on a collective scale rather than opting on the mainstream single-family approach.

2. Research Methodology

The proposed methodology places the building envelope at the core of a comprehensive mitigation strategy to tackle energy poverty risk in addition to other possible measures to support low-income people. However, this can be largely influenced by the scale and complexity of the involved building stock; therefore, some preliminary considerations have to be carefully taken into account. In order to make the process applicable to real market conditions with recurrent constraints—such as resource shortages—that often impede performing building works in one single step, especially on large stocks, the proposed methodology is based on a sequence of insulation steps involving increasing percentage of the building envelope surface. A preliminary analysis of a given building's type, shape, and configuration is needed to understand how many surfaces are affected by thermal dispersion. A rectangular-shaped building is of course less affected compared to a more irregular one, such as a U-shaped configuration. At the same time, a more irregular, complex structure may allow interventions to be split into smaller and more localized sites, adapted to the available resource capacity. It can be argued that this may become less economically convenient in the long run; however, the structural shortage of funding devoted to renovation—especially in publicly owned/managed stock—suggests that this can be the only viable option in many cases, ensuring a timely and budgeted multi-annual plan to complete the renovation of the whole building envelope.

According to these premises, our methodology envisages the following phases, which are summarized in Figure 1.

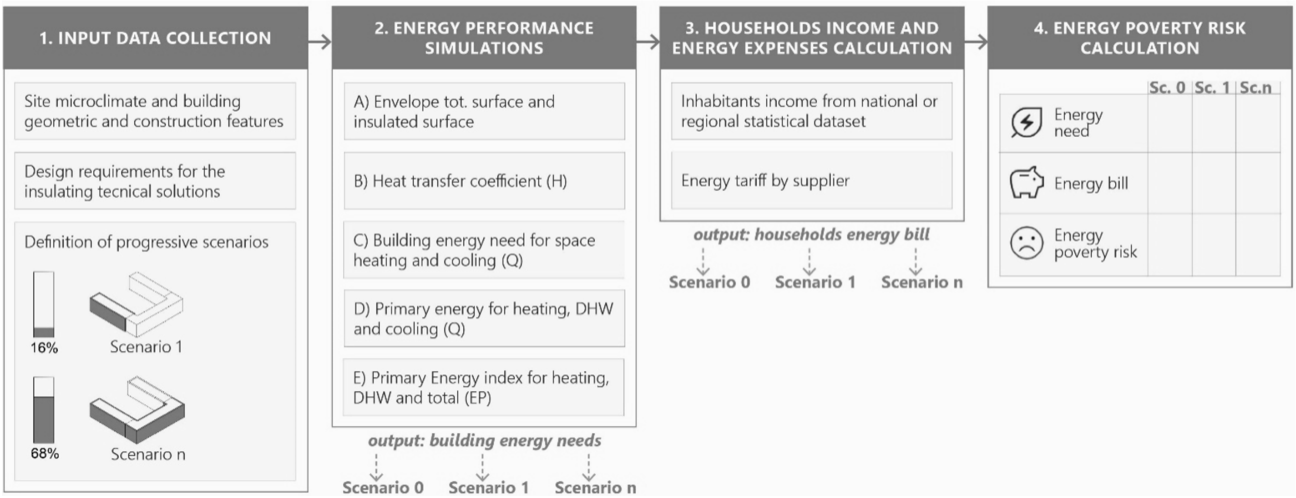


Figure 1. Flowchart of the methodology for comparing envelope insulation ratio and risk of energy poverty for households.

Phase 1—Input data collection. At this stage, some preliminary actions are performed: (i) analysis of the building configuration to define how many surfaces (façades/roofs) are involved and how many intervention steps are required; (ii) definition of the performance threshold (at least compliant with the one fixed by the local regulation) to make the building envelope able to effectively contribute to reducing thermal dispersion and the related energy demand; (iii) exploration of alternative design solutions able to achieve the same predefined threshold and selection of the most appropriate solution depending on technical and economical constraints; and (iv) generation of alternative scenarios of interventions.

Designed for large, multi-family buildings, this step initially considers the different façades (including both walls and glazed surfaces)—which are supposed to be widest surfaces involved in thermal dispersion—and then the roof and basement insulation.

A compulsory requirement is that the process can be implemented on the outer side of the building, thus preventing the need to move the inhabitants elsewhere (therefore reducing disruption to occupants, expenses, and related inconveniences) while limiting the impact of the renovation activities to a few days when the windows of each flat are replaced. This is a crucial element, especially in the case of social housing, where it is crucial for the managing company not to move the inhabitants to a different accommodation, which would represent not only an additional cost but also a strong barrier affecting the acceptance of the maintenance/renovation by the occupants.

Phase 2—Energy performance simulations. In order to meet the above-mentioned ambitions, two key assumptions are adopted before running the simulations: (i) A single technical solution for the insulation of the building envelope is defined for both the typical wall section and the frame of the glazed elements. To speed up the process compared to conventional options, the proposed technical solution is based on a preassembled insulating floor-to-floor module cladded by a metal sheet which protects the insulation layer and serves as a finishing. (ii) The percentage coverage of the building envelope is defined according to the volumetric configuration of the building in order to consider each single façade (considering the exposure and amount of glazed surface), the roof, and the basement, generating a suitable number of scenarios.

Each scenario is simulated following the UNITS 11300 [100] and ISO 13790 [101] standards, using Termolog simulation software v. 14 [102]. The following input data are inserted:

(A) Envelope surface, insulated surface, and first index are obtained;
(B) (Building heat transfer coefficient H'T), the following output is obtained per each scenario;
(C) Building energy needed for space heating ($Q_{H,nd}$) and cooling ($Q_{C,nd}$), expressed in kWh/yr;
(D) Primary energy for heating ($Q_{p,H,tot}$), domestic hot water ($Q_{p,W,tot}$), and cooling ($Q_{p,C,tot}$), expressed in kWh/yr;
(E) Primary energy index (EP) for heating ($EP_{H,tot}$), domestic hot water ($EP_{W,tot}$), and total ($EP_{gl,tot}$) for all energy services, expressed in kWh/m^{2}yr.

Phase 3—Household income and energy expense calculation. This phase is devoted to providing the following elements for each scenario:

(a) Family energy bills;
(b) Family energy bill effect and percentage of families under the poverty threshold;
(c) Total household cost, including rent and energy bills, and percentage of families under the energy poverty threshold.

Phase 4—Energy poverty risk calculation. The family income is extracted from the national or regional statistical institute dataset, ISTAT (Istituto Nazionale di Statistica, Italian National Institute of Statistics) in the case of Italy; energy tariff is provided by the supplier, which for local district heating in Italy is HERA [103]; and annual energy bills are calculated from primary energy results for each scenario.

Limitations of the Study

According to the described framework, the process intentionally focuses on the effect of envelope thermal insulation on reducing the risk of energy poverty; thus, no replacement or upgrade of the heating/cooling system is considered in the calculation. Moreover, the installation of renewable energy sources such as solar, thermal, or photovoltaic panels or alternative technology solutions such as district heating, which would require additional funding, are not considered at this stage to keep the cost analysis focused on the essential elements without including more sophisticated payback time calculations.

3. Case Study

Our methodology is practically simulated on a demo case of a vast social housing complex in Bologna, 44°49′ N latitude, 11°34′ E longitude, and 50 m a.s.l. altitude. According to the Köppen–Geiger [104,105] classification, the area falls under the humid subtropical (Cfa) Mediterranean climate, which is a humid climate with short dry summers and heavy precipitation occurring during mild winters. This corresponds to the Italian climatic 'zone E', where the estimated number of Degree Days (DDs) is between 2101 and 3000. More specifically, the estimated number of Degree Days in Bologna is 2259.

The building is located within a district north of the railway station, namely Bolognina, which has the highest rate of social housing in the city due to its historic vocation as a working-class neighborhood. Here, the city municipality and ACER Bologna (local social housing agency) have started a wide and ambitious program to renovate the stock while coping with climate change and social problems, including consumer vulnerability.

The demo case is a U-shaped building (Figure 2) included in a larger block forming two courtyards. It consists of 106 units distributed on five levels above the ground. The total floor surface is 1645 m^2, and the envelope surface is around 10,458 m^2. The underground garage, circulation spaces, and the eight staircases are not conditioned.

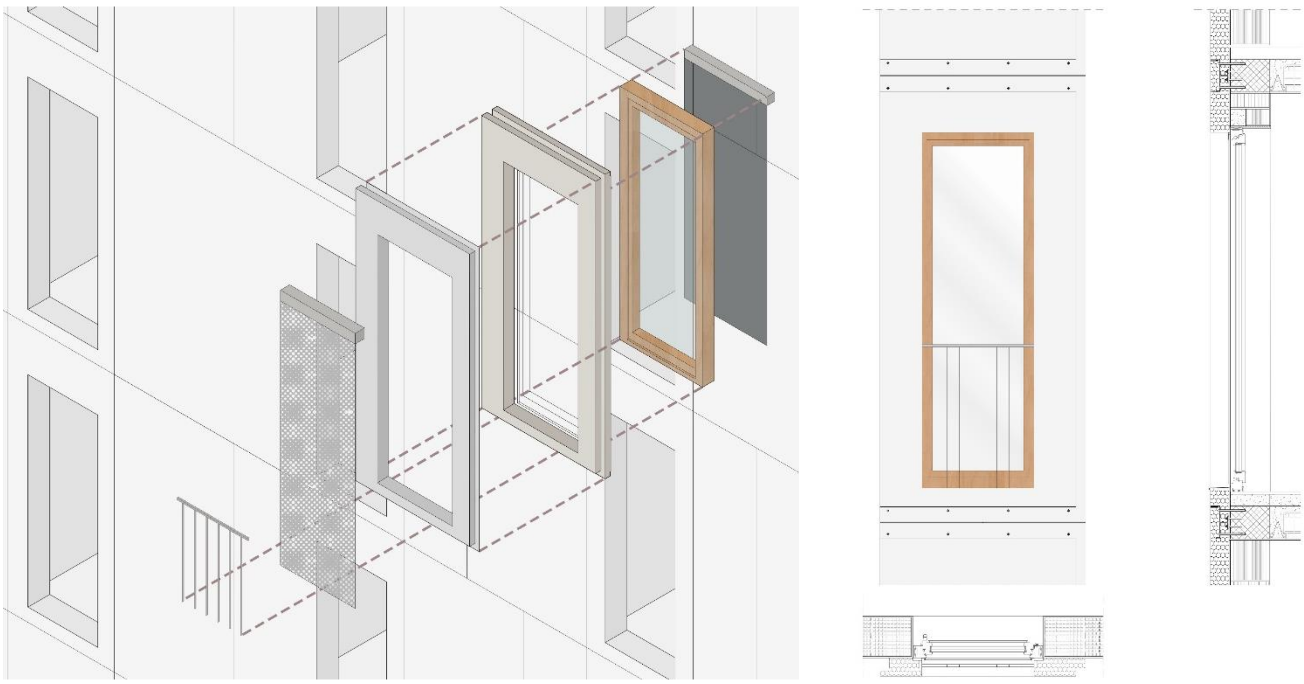
Figure 2. Aerial view of the area, with case study highlighted in red. Source: Bing maps.

The building has all the possible façade orientations: one southward, two facing west, one northward, and two facing east. The building has a reinforced concrete frame structure with hollow 30 cm thick brick block walls, with a plaster finishing of approximately 1.5 cm on both sides. The thermal transmittance [U] is 0.953 W/m^2K, very high compared to the current threshold fixed by the national regulation, which is 0.240 W/m^2K for the coldest climatic zone and 0.260 W/m^2K in the case of Bologna. Approximately the same poor performance is offered by the roof, which is made concrete sloped slabs with clay tiles.

An initial Termolog software simulation demonstrated that adding a 14 cm thick EPS insulation panel to the walls would allow the building to achieve a U value of 0.203 W/m^2K, which is a well-performing solution and largely meets the regulation targets even in case of future updates. It is worth noting that in Italy, the threshold limit for the coldest climatic zone shifted from 0.320 W/m^{2}K in 2010 to 0.240 W/m^{2}K in 2020, in only 10 years; thus, careful and forward-looking choices are preferable. In order to ensure a low-disruption renovation, both for occupants and the housing manager, who should otherwise reallocate them temporarily, the retrofitting solution is based on precast components.

Therefore, the proposed insulation solution is based on floor-to-floor modular panels of an expanded polystyrene (EPS) rigid element, with battens on each side to facilitate an efficient overlapping to prevent thermal bridges and a metal cladding which also acts as a finishing layer (and whose color may vary for aesthetic reasons according to the architectural façade pattern). A linear T-shaped insulated profile is to be fixed horizontally to the edge floor with a reinforced concrete beam of each level in order to ensure an efficient supporting element (mechanically anchored with steel bars) for the modules. For the demo case, three modules of different sizes were designed to meet the geometrical configuration of the façade, but this can be adjusted on a case-by-case basis. Two types of modules were needed to insulate the opaque surface of the façade, while the third one was to be integrated with the new glazed element. Dating back to thirty years ago, the existing windows showed signs of ageing, despite the wooden framework being equipped with double-paned glazing with an overall U value of 1.825 W/m^{2}K; therefore, we decided to replace them with better-performing ones of the same type and a triple-paned glazing (mm 4–15–4–18–4) with a final U value of 1.000 W/m^{2}K.

The linear profile as well as the modules can be installed quickly and easily without the use of scaffolding, working on small sky-walkers while each module is supported by a mobile crane. The solution can be easily disassembled in case a module requires replacing or needs specific maintenance for any reason (Figure 3a). The standard module reaches an overall weight of approximately 8 kg/m^2, but it is rigid and strong enough to self-support and avoid deformations during the installation process. Figure 3b illustrates the detailed design of the panel.



(**a**) (**b**)

Figure 3. On the left (**a**), a cross-section view of the precast panel components; on the right (**b**), a detailed design of the panel installed is provided. Elaborated by M. Falcone and S. Dellasantina.

Compared to traditional insulation, our solution allows for a reduction in installation time of 30 to 50% and saves 20 to 40% of costs depending on the complexity of the building configuration.

The roof is insulated by placing 16 cm thick EPS panels over the last floor slab under the pitched roof, while the ground floor slab is insulated by placing the same type of panels on the ceiling of the basement which hosts the car park. Table 1 summarizes the thermal transmittance of the different parts of the building envelope as they are currently and as designed in this study.

Table 1. Case study of thermal transmittance of the building technical units.

Building Technical Unit	U "As It Is" (W/m^{2}K)	U "As Designed" (W/m^{2}K)
Vertical opaque envelope	0.95	0.20
Windows	2.82	1.00
Ground floor slab	1.15	0.18
Attic slab	1.86	0.19

Dwellings are thus provided with thermal radiators and zone regulation, with 75% of heating system efficiency. Moreover, an electric boiler to produce domestic hot water with 75% energy efficiency is also considered. The building is not equipped with any cooling system.

The technical heating system is connected to the district heating with a primary energy factor of 1.5, so the final energy efficiency ratio between the energy need for heating and cooling and primary energy is 58%.

3.1. Average Household Bills, Income, and Energy Poverty Threshold

In this demo case, building energy performance simulations are limited to heating and domestic hot water (DHW) systems. Lighting and electric equipment are not considered as they are not dependent on the proposed improvements. Therefore, energy expenses are calculated without water and electricity costs.

Given that the neighborhood uses district heating, the energy tariff is retrieved from the related HERA portal—Navile [103].

Considering the impact of the pandemic and the Ukrainian–Russian conflict on inflation and gas prices, two values are assumed for the calculations:

- January 2021 (before the strong economic effects of the pandemic and before the conflict): EUR 0.066704/kWh;
- January 2023 (during recovery from the pandemic and conflict): EUR 0.161236/kWh.

These values were raised by 20% in the simulation to consider fixed costs and taxes.

Regarding income, the families who live in the considered building are typically low-income, which is an entry requirement to access publicly owned houses. Indeed, ACER Bologna sets rent based on the equivalent indicator of the economic situation of the family (in Italy, this takes the acronym ISEE). So, statistical data on the income of potential occupants of the building have been retrieved from Iperbole [106], a city-dedicated web portal. The average income of Bolognina's inhabitants (average 2019–2022) was EUR 23,080 for Italians and EUR 12,125 for migrants, with a district average income of EUR 21,062.

Lastly, following the OIPE report [12], an energy poverty threshold of 6% is considered for the simulation.

3.2. Building Envelope Insulation Scenarios

According to our methodology, progressive insulation scenarios were simulated considering the geometry of the building. Therefore, the following steps were identified:

- Scenario 0—Current state with no insulation (0% of opaque and transparent envelope);
- Scenario 1—Vertical closure insulation of the building's west wing (16% of the opaque and transparent envelope);
- Scenario 2—Vertical closure insulation of the south wing (53% of the opaque and transparent envelope);

- Scenario 3—Vertical closure insulation of the east wing (68% of the opaque and transparent envelope);
- Scenario 4—Whole-volume roof insulation (84% of the opaque and transparent envelope);
- Scenario 5—Ground floor insulation (100% of the opaque and transparent envelope).

4. Results

The results of the simulation are presented according to the key steps of the methodology. Hence, the energy performance of each scenario is illustrated first, followed by a comparison with potential energy bills and household income to evaluate the inhabitants' risk of falling into energy poverty in each scenario.

4.1. Energy Performance Results

Table 2 illustrates the results of the energy needs simulations for each scenario, performed in Termolog. Scenarios are compared in columns, while rows report the following:

A. Building input data: E, total surface of heat dispersant envelope; I, the insulated surface corresponding to the relative scenario; their ratio (I/E) is expressed as a percentage. Therefore, I/E = 0% is the current state, with no insulated surfaces, and I/E = 100% is the best scenario in which the entire envelope is insulated (including the roof, basement, and window replacement);
B. Building heat transfer coefficient by transmission (H), expressed in W/K. H_d is the transmission heat transfer between the conditioned space and the external environment; H_u is the coefficient between the conditioned and adjacent unconditioned zones (e.g., attic and garage); $H_{tot} = H_d + H_u$; and H'T is a coefficient resulting from the ratio between H_{tot} and E (envelope surface), measured in W/m^2K;
C. Energy needs (as thermal power) for heating and cooling, following ISO 13790, divided into energy needs for heating ($Q_{H,nd}$) and cooling ($Q_{C,nd}$) expressed in kW;
D. Primary energy expressed in kWh/year, divided into heating ($Q_{p,H,tot}$), DHW ($Q_{p,W,tot}$) and total ($Q_{p,gl,TOT}$);
E. Primary Energy index for heating (EP_H), DHW (EP_W), and total ($EP_{gl,TOT}$), expressed in kWh/m^2year.

Table 2. Building energy performance simulation results for each scenario.

	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
(A) Building input data						
E: Total envelope surface (m^2)	10,458	10,458	10,458	10,458	10,458	10,458
I: Insulated surface (m^2)	0	1638	5521	7159	8804	10,458
Ratio I/E (% insulated surface/total)	0%	16%	53%	68%	84%	100%
(B) Building heat transfer						
H_d (W/K)	5177.28	4152.73	2473.10	1545.38	1545.38	1545.38
H_u (W/K)	6220.45	6204.54	6209.83	6210.21	3706.45	2555.77
H_{tot} (W/K)	11,397.73	10,357.27	8682.93	7755.59	5251.82	4101.15
H'T (W/m^2K)	1.09	0.99	0.83	0.74	0.50	0.39
H't decrease compared to Sc. 0 (%)	**0%**	**9%**	**24%**	**32%**	**54%**	**64%**
(C) Energy needs for heating and cooling						
$Q_{H,nd}$ (kW)	2174.77	1979.72	1702.77	1530.48	1069.28	952.66
$Q_{C,nd}$ (kW)	69.79	44.58	28.72	8.16	9.25	10.91
(D) Primary energy						
$Q_{p,H,tot}$ (kWh/yr)	104,5364	941,535.1	810,394.5	724,288.2	508,068	451,601.2
$Q_{p,W,tot}$ (kWh/yr)	9111.1	8882.8	8514.1	8284.7	7815	7691.3
$Q_{p,gl,TOT}$ (kWh/yr)	1,054,475.1	950,417.9	818,908.6	732,572.8	515,883.4	459,292.5
(E) Energy index EP						
EP_H (kWh/m^2yr)	157.53	142.21	122.4	109.4	76.74	68.21
EP_W (kWh/m^2yr)	1.37	1.34	1.29	1.25	1.18	1.16
$EP_{gl,TOT}$ (kWh/m^2yr)	158.91	143.55	123.69	110.65	77.92	69.37
$EP_{gl,TOT}$ decrease compared to Sc. 0 (%)	**0%**	**10%**	**22%**	**30%**	**51%**	**56%**

Figure 4 shows that as H'T decreases, building envelope insulation increases and heating power decreases almost linearly (orange line). On the right, cooling power (blue line) also decreases, except for scenarios 4 and 5 (respectively, 84% and 100% insulated envelope), where a slight increase is registered. These also include insulation of the garage and attic, which is a bit disadvantageous for cooling.

Figure 4. Relationship between the building heat transfer coefficient H'T and power for heating (H, on the right) and cooling (C, on the left).

In any case, a significant difference is recorded between heating and cooling power, e.g., in the best scenario (n.5), the building's demand for heating is 952 kW (about 9 kW for each unit) and only 11 kW for cooling. This depends on the building's geometry, the presence of an attic, and the limited impact of windows (which are less than 8% of the total envelope surface).

Figure 5 illustrates the same data but considers the percentage of the envelope that is insulated instead of the heat transfer coefficient. The heating and cooling power trends are inverse to those shown in Figure 4. Figure 6 shows the EP index trend in relation to the percentage of the envelope that is insulated. The trend is in line with the previous results, dropping down from 158 kWh/m^{2}yr (sc. 0) to 69 kWh/m^{2}yr (sc. 5) with an overall reduction of 56%. The insulation of façades only (including windows replacement) produces an energy poverty reduction of 30%.

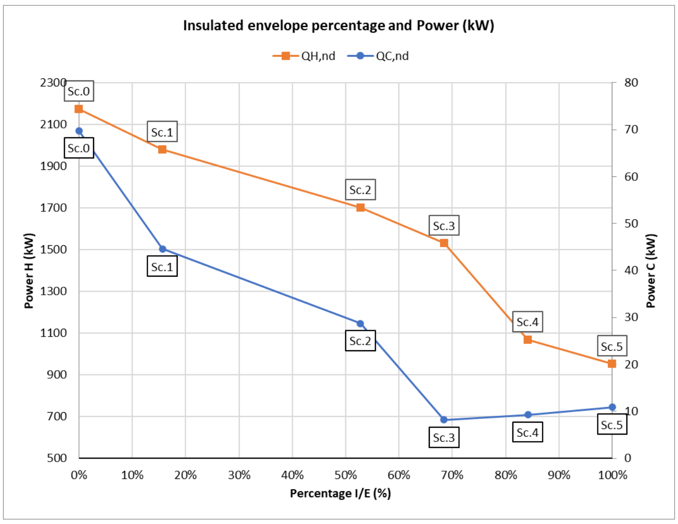


Figure 5. Relationship between the insulated envelope percentage (%) and power for heating (H, on the right) and cooling (C, on the left).

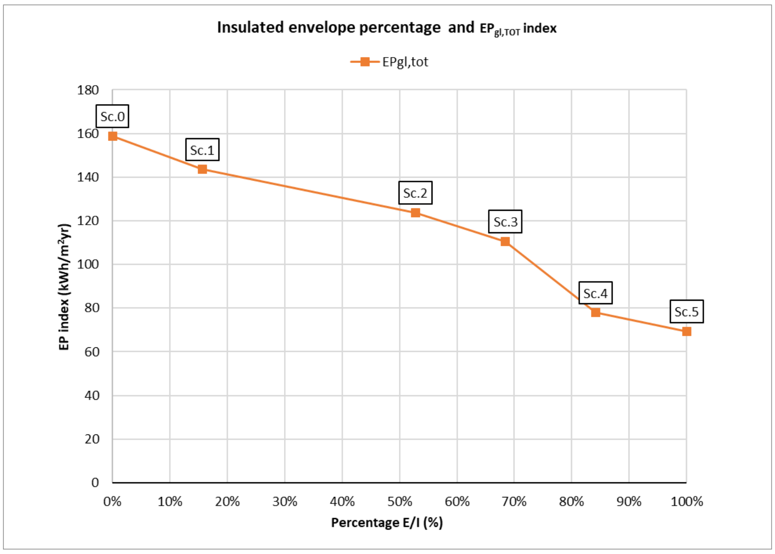


Figure 6. Relationship between the insulated envelope percentage (%) and EP index (kWh/m^{2}yr).

4.2. Energy Poverty Risk

The last step of our methodology was to calculate the risk of energy poverty related to each scenario. Both 2021 and 2023 energy tariffs were included in the simulation and the results are shown in Tables 3–5. What follows is a detailed description of the results for 2023 as the most recent and representative year. At present, the total annual energy expenditure to meet heating needs is EUR 204,373 per year. Considering that the building consists of 106 units (dwellings), it is estimated that each family currently spends approximately EUR 1920 per year for heating and hot water alone. The simulation demonstrated this cost would drop to EUR 838/yr if the envelope was entirely insulated (sc. 5), which corresponds to a yearly saving of EUR 1086 per household.

Table 3. Comparison of energy expenditures for each scenario.

			2021			
	Scenario 0	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
EUR/building/year	EUR 84,216	EUR 76,076	EUR 65,551	EUR 58,640	EUR 41,294	EUR 36,763
EUR/unit/year	EUR 794	EUR 718	EUR 618	EUR 553	EUR 390	EUR 347
			2023			
	Scenario 0	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
EUR/building/year	EUR 203,566	EUR 183,889	EUR 158,448	EUR 141,744	EUR 99,816	EUR 88,864
EUR/unit/year	EUR 1920	EUR 1735	EUR 1495	EUR 1337	EUR 942	EUR 838

Table 4. Percentage of heating expenses based on various average incomes. Values highlighted in red are those overcoming the energy poverty threshold.

			2021			
Family income in Bolognina	**Scenario 0**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
EUR 12,125 migrants	6.55%	5.92%	5.10%	4.56%	3.21%	2.86%
EUR 21,062 total	3.77%	3.41%	2.94%	2.63%	1.85%	1.65%
EUR 23,080 Italians	3.44%	3.11%	2.68%	2.40%	1.69%	1.50%
			2023			
Family income in Bolognina	**Scenario 0**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
EUR 12,125 migrants	15.84%	14.31%	12.33%	11.03%	7.77%	6.91%
EUR 21,062 total	9.12%	8.24%	7.10%	6.35%	4.47%	3.98%
EUR 23,080 Italians	8.32%	7.52%	6.48%	5.79%	4.08%	3.63%

Table 5. Comparison of monthly rent and annual heating and hot water expenditures and percentage decrease for each scenario compared to scenario 0.

2021						
Rent per month	**Scenario 0**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
EUR 50	EUR 1394	EUR 1318	EUR 1218	EUR 1153	EUR 990	EUR 947
	0%	6%	13%	17%	29%	32%
EUR 100	EUR 1994	EUR 1918	EUR 1818	EUR 1753	EUR 1590	EUR 1547
	0%	4%	9%	12%	20%	22%
EUR 150	EUR 2594	EUR 2518	EUR 2418	EUR 2353	EUR 2190	EUR 2147
	0%	3%	7%	9%	16%	17%
EUR 200	EUR 3194	EUR 3118	EUR 3018	EUR 2953	EUR 2790	EUR 2747
	0%	2%	6%	8%	13%	14%
EUR 250	EUR 3794	EUR 3718	EUR 3618	EUR 3553	EUR 3390	EUR 3347
	0%	2%	5%	6%	11%	12%
EUR 300	EUR 4394	EUR 4318	EUR 4218	EUR 4153	EUR 3990	EUR 3947
	0%	2%	4%	5%	9%	10%
EUR 350	EUR 4994	EUR 4918	EUR 4818	EUR 4753	EUR 4590	EUR 4547
	0%	2%	4%	5%	8%	9%
EUR 400	EUR 5594	EUR 5518	EUR 5418	EUR 5353	EUR 5190	EUR 5147
	0%	1%	3%	4%	7%	8%
2023						
Rent per month	**Scenario 0**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
EUR 50	EUR 2520	EUR 2335	EUR 2095	EUR 1937	EUR 1542	EUR 1438
	0%	7%	17%	23%	39%	43%
EUR 100	EUR 3120	EUR 2935	EUR 2695	EUR 2537	EUR 2142	EUR 2038
	0%	6%	14%	19%	31%	35%
EUR 150	EUR 3720	EUR 3535	EUR 3295	EUR 3137	EUR 2742	EUR 2638
	0%	5%	11%	16%	26%	29%
EUR 200	EUR 4320	EUR 4135	EUR 3895	EUR 3737	EUR 3342	EUR 3238
	0%	4%	10%	13%	23%	25%
EUR 250	EUR 4920	EUR 4735	EUR 4495	EUR 4337	EUR 3942	EUR 3838
	0%	4%	9%	12%	20%	22%
EUR 300	EUR 5520	EUR 5335	EUR 5095	EUR 4937	EUR 4542	EUR 4438
	0%	3%	8%	11%	18%	20%
EUR 350	EUR 6120	EUR 5935	EUR 5695	EUR 5537	EUR 5142	EUR 5038
	0%	3%	7%	10%	16%	18%
EUR 400	EUR 6720	EUR 6535	EUR 6295	EUR 6137	EUR 5742	EUR 5638
	0%	3%	6%	9%	15%	16%

Taking as a reference the total average income of Bolognina residents, which is equal to EUR 21,062, this means that households currently spend 9.25% of their income on building heating needs. In scenarios 4 and 5, this ratio is reduced to less than 5%. In other words, the last two interventions would ensure no household in the building would be at risk of energy poverty. Contrarily, in cases 1 to 3, the energy poverty index is still above the threshold of 6% (Table 4).

As mentioned, families living in ACER buildings have a very low income and their rent is defined according to their ISEE, including housing assets and quality parameters, so it is difficult to identify the specific amount they would pay for rent. However, Table 5 shows an assumption of "Rent cost/year" + "Energy bill cost/year" for heating and domestic hot water based on various income brackets. The assumed rents range from EUR 50 to EUR 400 per month. For each rent (in row) and intervention scenario (in column), the housing cost (rent cost per year + energy bill) as well as the percentage of annual cost savings that can be achieved thanks to the intervention are estimated.

In the case of the lowest rent (EUR 50/month, that is EUR 600/year), between the current situation and the complete envelope retrofit scenario (no. 5), a saving of 43% is registered. This accounts for about EUR 1086/yr, which can be reallocated to other family expenses (e.g., food, clothes, health). In the case of the highest considered rent (EUR 400/month—EUR 4800/year), there is a saving of 16%.

5. Discussion

The results show a correlation between the percentage of the building envelope that is insulated and the heating/cooling energy needs variation. In general, it can be observed that as the former increases, the latter decrease. However, this trend is not linear, so it is not that easy to predict, and some interesting exceptions deserve to be discussed further.

For instance, the slight increase in energy needs for cooling in scenarios 4 and 5 compared to the previous scenarios is interesting to note. This is likely because ground thermal properties that allow for cooler air temperatures in the garage and a cooling effect due to ventilation in the attic are absent in these scenarios. Considering rising temperatures due to climate change, it will become increasingly important to take into account cooling needs too when addressing energy poverty. In line with most recent studies, this shift in energy demand patterns can not only significantly impact the energy poverty risks of low-income families, but it can also extend the risk to other households living in poorly equipped dwellings due to differences in the efficiency of heating and cooling systems, meaning that shifting a certain share of energy demand from winter to summer may significantly change the cost expenditure. Not to mention the potential impacts that a bulk request of energy for cooling may have on the energy grid, with a significant increase in blackouts and consequent effects on fragile individuals, who are very often poor and very poor. Thus, even if the last two scenarios (4 and 5) allow for a significant reduction in energy needs, their side effect on cooling should be addressed on a case-by-case basis. On the other hand, scenarios 1 to 3 produce an energy demand reduction of less than 30%, which does not ensure all households are prevented from falling into energy poverty in spite of investing into façade energy retrofitting.

Moreover, the results show that the energy need reduction achieved through envelope insulation would not be enough to improve the building's overall energy performance to the highest energy classes foreseen in Italian regulations [107,108], but it would at least allow the building's energy consumption to be halved. A linear correlation between H'_T decrease and $EP_{gl,tot}$ decrease is evident in the diagrams.

In this study, the contribution of the technical heating system is not considered in the calculation—a 58% efficiency ratio is assumed in all scenarios—but its upgrading or replacement might help to reduce the energy demand further. Should the technical system efficiency improve, for instance by disconnecting from district heating and using a heat pump or implementing on-site renewables, the same decreasing trend in primary energy might be expected for all scenarios (ref. Table 2). If suppose the energy efficiency ratio improves by 80% rather than 58%, e.g., with the use of a heat pump, the same improvement can be obtained for each scenario. That is why the energy efficiency ratio has not been considered as a variable in this study.

Concerning energy poverty risks, a major role of energy prices and family income emerges from Table 3: with lower energy prices (2021), the demo case is an energy poverty risk building only for migrant families in Bolognina, while considering the raised tariffs of 2023, it becomes an energy poverty risk building in every scenario, except in sc. 3, 4, and 5 for Italians who have higher average incomes.

Table 5 also confirm the role of energy prices in strongly rising energy poverty risks for households. With a possible monthly rent equal to EUR 50, a decrease of 36% in rent plus energy cost is estimated for 2021 energy prices, decreasing up to 43% for the 2023 energy tariff. In the case of a monthly rent equal to EUR 400, an 8% decrease can be observed in the case of 2021 energy prices and a 16% decrease in the case of 2023 prices.

It can be thus affirmed that energy cost has a major effect when rent per month is lower, while energy prices have a major role when rent per month is higher.

These fluctuations suggest that the potential benefit coming from building envelope insulation in the long run should be considered more carefully. Special subsidies should be limited to only compensate for tariff peaks while tackling the recurrent rise in prices on the competitive market through more stable and durable investments is recommended.

6. Conclusions

This article reports a study which correlates the impact of energy retrofitting interventions with the risk of falling into energy poverty for households, which is still underestimated both in the literature and dedicated energy poverty policies. In particular, this study correlates diverse percentages of building envelope insulation to family income in order to examine the advantages of incremental solutions versus one-time investments or subsidies in reducing the impact of energy poverty. In order to make the possible impacts of the proposed method clearer, a demo case is used to test the process, which can be replicated for other countries, considering alternative income ranges and economic trends depending on the local context.

The main significance of the proposed investigation lies in the shift of attention from occasional and income-related subsidy measures to more stable and building-related solutions with reference to their potential mitigation effect of energy poverty risk. In line with the New European Bauhaus manifesto, this approach places the quality of the built environment at the core of the process, suggesting stable investments for improving the performance of the building envelope to prevent end-users from adopting unhealthy behaviors or becoming prone to energy poverty due to external factors they cannot directly manage. The scope is not to cancel the adoption of occasional individual supporting measures, which can be vital in the case of extreme price conditions, but to stress their extraordinary nature and the need of multi-annual plans able to impact many subjects at once.

Therefore, this study considers only the possible contribution of building envelope insulation, but future stages might involve applications aimed at retrofitting heating/cooling systems as well, with the goal of further improving living conditions. Furthermore, no life cycle cost analysis or speculations regarding the service life of components and systems were performed at this stage, as the primary scope was to highlight the relevance of the building envelope in mitigating/reducing energy poverty risk when assigning funding or supporting measures, but these elements can be certainly added to possibly address the most cost-effective and sustainable solutions possible.

This study is specifically intended to raise awareness of the research community and policymakers about the role of buildings and building envelope qualities in combating energy poverty. Indeed, even if subsidies and special energy tariffs for vulnerable consumers can be valuable in the short term, in the long run, it is more effective and rewarding for both public and private entities to act on structural factors such as building inefficiencies (e.g., envelope, systems).

The authors are aware of the difficulties and constraints affecting the feasibility of building renovation, which in the short-term perspective are more expensive than energy price policies for poor families, but considering the overall EU policy framework and other drivers boosting the renovation rate of the existing stock, the proposed approach sounds more suitable and potentially more effective in considering the energy poverty issue from a more comprehensive perspective. The main limitation of the current policies in many countries is indeed that the mitigative power of alleviating measures quickly disappears when the incentives are suspended or canceled for any reason (e.g., the Italian PNIEC established an energy bonus to help poor families, but this depends on the annual national financial document), whilst the European Commission is now encouraging Member States to adopt forward-looking, structural, and inclusive measures. This expected mindset shift is also the result of an evolving understanding of inclusion, sense of community, and just transition promoted by the United Nations' global Sustainable Development Agenda, which aims at eradicating societal problems rather than temporarily alleviating them by means of incentives.

That is why the proposed study does not include renovation costs in the final balance as it is supposed that these are covered by dedicated funds for social housing, which in Italy represent a very small part of the massive financial incentives that were released during the last three years to support deep insulation of building façades, namely the Superbonus [109,110]. This would lead to a further reflection on how public resources are allocated and on how interventions are prioritized. As this is a specific situation in the Italian context, it was not within the original scope of the article, which aims to unveil how technical and economic issues are interconnected in this very urgent and socially relevant field. The authors do hope that once the relevance of the issue is recognized, the new Energy Performance of Building Directive (Recast IV) will strongly support building retrofitting as a way to act against energy poverty.

Author Contributions: Conceptualization, J.G., K.F., L.M. and E.A.; methodology, J.G., K.F. and L.M.; formal analysis, K.F. and L.M.; investigation, J.G., K.F., L.M. and E.A.; resources, J.G., K.F. and L.M.; data curation, K.F. and L.M.; writing—original draft preparation, J.G., K.F. and L.M.; writing—review and editing, J.G., L.M. and E.A.; supervision, J.G. and E.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors thank Michela Falcone and Syria della Santina for contributing to the data collection and energy calculation stages.

Conflicts of Interest: The authors declare no conflict of interest.

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