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Energy efficiency in the polish residential building stock: A literature review

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ABSTRACT

The Polish energy market heavily relies on coal. Pressured by the European Union, the Polish government has recently decided to accelerate coal phase-out and to gradually shut down all coal mines by 2049. In that context, it is necessary to assess the Polish energy market's state regarding energy efficiency, especially in the building stock. This paper aims to provide an overview of the current state of energy efficiency of residential buildings in Poland and insights into its future trends. A literature review was conducted, accompanied by focus group discussions with Polish building energy efficiency experts. The Polish energy sector is under a remarkable transformation that may be going too fast. A large gap between expectations, practices, and requirements can be observed. Raising awareness and capacity building in the energy efficiency sector, and a set of accessible guidelines should be developed so that the transformation is implemented correctly. A SWOT analysis results define the key opportunities and threats that are critical to meet net-zero emissions goals. The paper provides findings and insights on the 2020 targets status quo and raises awareness among stakeholders and fills a knowledge gap regarding energy efficiency in the Polish residential building stock.

1. Introduction

The Polish energy market heavily relies on coal. The country is under the European Union policies' pressure and has recently decided to accelerate coal phase-out. It plans to gradually shut down all coal mines by 2049. Simultaneously, Poland has one the fastest growing economies in the Euro Zone. The construction sector is expected to grow. According to the European Construction Sector Observatory (ECSO), the growth is expected to reach 5.4% between 2020 and 2021 [1]. This trend is confirmed when looking at the numbers of commissioned apartments in 2014–2018. The rapid growth benefited from a consistent set of policies and strides in decarbonizing its energy sector. The Polish buildings sector's decarbonization is vital to deliver on the E.U.s 2030 and 2050 climate and energy objectives. In Poland, buildings are responsible for 38% of total energy consumption [2] and 33% of energy-related greenhouse gas emissions [3]. The residential sector in Poland relies on solid fuels more than in any other EU country (see Fig. 1). The deterioration of ambient air quality and securing and diversifying energy supply could jeopardize the country's progress toward energy efficiency [4].

Energy efficiency is an essential component for action, and the building sector is one of the areas where efforts must be ramped up. To achieve a European net 55% emission reduction target by 2030, Poland needs to reduce buildings' energy-related greenhouse gas emissions by 20% compared to 2015 levels and not only 7% as indicated in the final integrated national energy and climate plan (NECP) [5].

In terms of energy efficiency progress in the household sector over 2008–2018, Poland was ranked 21st among the EU. With a 1.13%/year rate of energy efficiency improvements, Polish households were below the EU's average and far below the improvements rate achieved by Poland's industry [8]. Poland is implementing several energy efficacy measures in multifamily buildings and has an energy efficiency obligation scheme [9]. The residential sector is the largest energy consumer, driven mainly by single-family buildings [10]. According to the [8] National Energy Conservation Agency (KAPE), almost half of

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Abbreviations:

AAC	Autoclaved Aerated Concrete
AC	Air conditioning
BPIE	Building Performance Institute Europe
DHW	Domestic Hot Water
ECSO	European Construction Sector Observatory
EE	Energy Efficiency
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificates
ETICS	External Thermal Insulation Construction System
ETS	Emissions Trading System
EU	European Union
FGD	Focus Group Discussions
GAHE	Ground Air Heat Exchanger
HVAC	Heating Ventilation and Air Conditioning
KAPE	Polish National Energy Conservation Agency
LPG	Liquefied petroleum gas
NAPE	National Energy Conservation Agency
nZEB	nearly Zero Energy Buildings
NZEB	Net Zero Energy Buildings
PH	Passive House
SWOT	Strengths Weaknesses Opportunities Threats
PCM	Phase Change Material
PH	Passive House
PV	Photovoltaic
RES	Renewable Energy Systems
SRI	Smart Readiness Indicator
VET	Vocational Education and Training

households (5.5 million households) live in single-family households [11]. Most single-family households rely mostly on coal, biomass, and waste for heating and domestic hot water (DHW). The report of KAPE is part of the TABULA project (Typology Approach for Building Stock Energy Assessment) aimed to develop a general overview of the Polish buildings' energy performance. The TABULA project grouped residential buildings in Poland under four different main building categories: single-family houses (SFH), terraced houses (TH), multifamily houses (MFH), and apartment blocks. Each category was split up between seven buildings representing typical building traditions and insulation levels [11].

In that context, it is necessary to assess the Polish energy market's state regarding energy efficiency, especially in the residential building stock, as it is one of the main polluting industries. This paper aims to provide a snapshot of the current state of energy efficiency in Poland's residential buildings. The objectives of this paper are as follows: 1) to determine the main screen and review the main publications that describe the energy efficiency of the Polish residential sector, 2) to identify the strengths, weaknesses, opportunities, and threats that Poland faces towards energy and carbon-neutral residential building stock, and 3) to generate knowledge based on insights and provide recommendations towards nearly zero energy residential buildings. The research questions corresponding to the objectives are as follows:

1. To what extent are the issues related to cost, energy sources, policies, education, air quality, and technologies of energy-efficient buildings in Poland addressed in literature?
2. What are the strengths, weaknesses, opportunities, and threats of Polish energy efficiency policies and practices in the residential sector?
3. What are the recommendations to improve the Polish residential building's energy efficiency towards nZEB and in line with the EPBD 2050 targets?

Thus, a current literature review based on content analysis and focus group discussions is presented. The findings offer an updated overview of the Polish residential sector's energy efficiency was based on reviewing 100 publications. This is the first literature review on energy efficiency in the Polish residential building sector to the best of our knowledge. The review succeeded in identifying the most vital instruments and promising opportunities that Poland shall capitalize to achieve the EU EPBD targets. Implementing the study recommendations may help to strengthen the institutional capacity and guide financing policies. Moreover, the focus group discussion with 14 Polish experts allowed validating the findings and presenting insights on the status quo of Poland's energy efficiency. The insights of this research can inform building engineers, operators, owners, manufacturers and identify the most promising actions and measures according to experts.

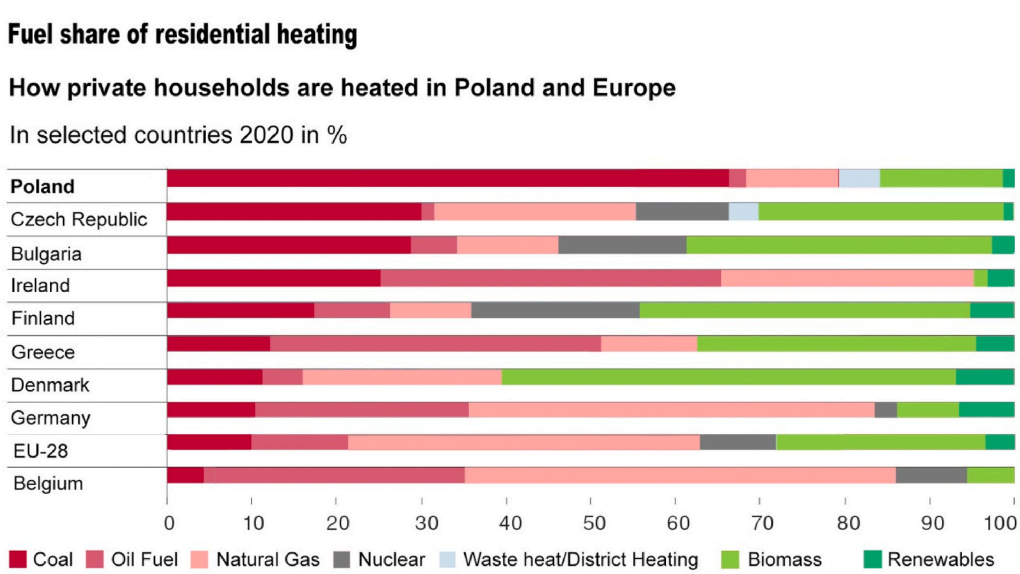

Fig. 1. Fuel share of residential heating in Europe [6,7].

The first section of this paper presents the methodology used to conduct the research. The second section offers the results of the extensive literature review, and the fourth provides the results of the focus group discussions. The last section of the paper summarizes the main findings, provides recommendations and assesses the study's strengths and limits and its implication on future research.

2. Methodology

The methodology used in this paper is qualitative and is similar to the previous work conducted by Muresan et al. (2017) [12]. The study combines literature reviews and focus group discussions (FGD). Both were conducted to evaluate the state-of-art and future trends of energy efficiency of residential buildings in Poland.

The literature review analysis was performed by browsing through key references related to residential buildings' energy efficiency. Fig. 2 illustrates the keyword used as part of the inclusion criteria in the literature search. To elaborate the review, Google Scholar, Elsevier Engineering Village, and Web of Science database searches were conducted during February 2020. Documents from key institutions, such as the European Construction Sector Observatory (ECSO) and Polish National Energy Conservation Agency (KAPE) were also gathered. The search included publications found in the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) and the proceedings of International Building Performance Simulation Association (IBPSA) conferences and International Buildings Physics Conferences (IBPC). More than eighty references were collected, including journal papers, reports, and English and Polish articles. The second step of the literature review was to narrow the number of references down. The focus was placed on publications related to building envelope, the inhabitants' well-being, and Poland's policies. The literature review inclusion criteria included several terms related to the European Energy Performance of Buildings Directive (EPBD), such as 'certification','cost-optimal', 'nearly Zero Energy Buildings (nZEB)' and 'Net Zero Energy Buildings (NZEB).'The length of the references and the quality of the sources were also selection criteria. The final literature review survey list was elaborated by selecting references associated with the main parameters that influence Poland's energy efficiency (see Table A inAppendix I). The last step of the literature review was to create a literature review matrix that summarizes the study's main findings. The references were sorted according to seven main criteria: economy, energy sources, policies and regulations, education and skills, comfort, outdoor air quality, and building technologies. Fig. 2 shows these key elements that significantly impact the building energy efficiency of the residential sector.

Fig. 2. Key elements influencing energy efficiency in Poland.

The second part of the methodology was to conduct focus group discussions. The focus group discussions were administered as a joint exercise similar to Refs. [13,14]. With the guidance of a facilitator, we identified the barriers to increasing the market uptake of energy efficiency in residential buildings and understand the gaps between theory and practice in reality. The output of the FGD was in the form of a report, which was developed via participant consensus to reflect the key steps and roadblocks identified during the panel conversations with the academic and industrial experts. Participants of the FGD were identified based on their practice in representing policy-making institutes and engineering and architectural firms. Table A in Appendix I was used to identifying the most productive scientific researchers working in the field of building energy efficiency in Poland. Three focus groups were conducted during three workshops of the ZERO projects in the summer of 2020 and 2021. FGD (overall 14 participants) were held on July 28th and 30th of 2020 in Warsaw and Gdańsk and on the 5th of October 2021 online.

Research themes analyzed FGD transcripts to identify and understand the reality of the energy efficiency of residential buildings. The market uptake of high-performance buildings and their associated technologies and their potential was discussed. As a result, a SWOT analysis was performed. This analysis underlines the main strengths, weaknesses, opportunities, and threats related to Polands' energy efficiency.

3. Literature review

The main results of the literature review are summarized below. The analysis grouped the key publications related to the Polish residential sector energy efficiency under the following sub-sections:

3.1. To what extent are the cost and financial factors addressed in buildings energy efficiency studies in Poland?

Few studies and reports on the financial factors of buildings' energy efficiency in Poland were found in the literature. In 2013, the Building Performance Institute Europe (BPIE) published a study implementing Poland's cost-optimality methodology [15]. The study found a significant gap between the U-values calculated with the EU cost-optimal methodology [16] and the U-values of the current Polish regulations. Polands' required U-values are higher than those mandated by the cost-optimal approach for both gas and coal as an energy carrier.

In 2015 Basinska et al. [17] conducted a sensitivity analysis to determine the optimum energy for residential buildings in Polish conditions over 30 years. Polish standards were applied to the buildings' energy performance [18,19]. The authors applied a global costs calculation method using single-family and multifamily households. Twenty-eight different technical variants for one building were defined, including the envelope, HVAC systems, and economic variants of energy sources and prices. However, the study did not develop specific recommendations or rank the energy efficiency measures concerning payback time or cost-effectiveness. Moreover, the study did not adopt the E.U. cost optimality approach and was mainly based on the 2008 energy efficiency standards [18].

In 2016, the Buildings Performance Institute Europe (BPIE) published a status report on financing building energy performance improvement in Poland [20]. The report listed operational funding schemes, including the Thermo-modernization Fund and RYŚ Fund and the Clean Air Fund (2018–2029), KAWKA, and SMEs funding programs that focus on light renovation. The review included the National Fund for Environmental Protection and Water Management (NFEP&WM). The study characterized the key renovation technologies in Poland and investigated three renovation scenarios to compare with the current activity level.

In 2019, Firląg [21] conducted a cost optimality study on single-family houses' energy performance. This papers' main objective was to propose Plus Energy Buildings (PEB) requirements in Poland. The study was based on the Polish energy efficiency requirement of 2015 [18]. Energy efficiency and renewable variants were applied in thermal insulation elements, ventilation systems, and heating systems. The paper provided valuable recommendations regarding the new regulations to be released in 2021, which mandate that the coefficient of annual energy demand for non-renewable primary energy – including heating, ventilation, cooling, domestic hot water preparation, and lighting - should not exceed 70 kWh/m^2.year. However, the study did not determine cost-optimal levels used in the Polish regulation to set the energy efficiency requirements.

More recently, Adamczyk et al. (2020) [22] investigated the economic benefits of the medium-level Thermo-Modernization of single-family buildings. The study conclusion confirms the lack of financial benefits for house owners regarding the medium-level thermo-modernization. Compared to coal, biomass, and waste boilers, the high cost of efficient boilers (natural gas boiler and fuel oil boiler) impede any breakthrough or economic benefit for deep renovations. Also, Gołąbeska [23] calculated the costs of constructing and maintaining a PH-certified house and the invested capital payback time. The study confirmed the challenging financial benefit and the high initial cost compared to conventional buildings. The study confirmed the PH concept's financial soundness only when calculating long-term operational costs exceeding 30 years. The findings are confirmed by the study of Księżopolski et al. (2020) [8], who investigated the energy and financial savings potential of renovating rural single-family houses in Poland. The energy conservation measures addressed the envelope performance improvement and replacement of the coal boilers to gas, electricity, and heat pump/PV installations. The results proved that the heat pump driven by PV installation operating in the Polish Prosumer support mechanism framework is the most cost-effective way of heating SFH buildings. However, without green subsidies and financial support, heat pumps and PV are not cost-effective. Surprisingly, the three studies' research methods did not follow the EU cost optimality approach [24]. The studies succeeded in embedding the green subsidies and financial support funding assumptions in Poland's cost-effectiveness calculations. However, the studies remain none representative regarding the selection of national archetypes, which should have been based on the Polish building typology characterization [11]. Moreover, the future renovation or new construction scenarios did not align with future energy efficiency regulation and EPBD requirements nearly and net-zero energy buildings.

Hence, the EU-based approach to adopt the cost-optimal methodology to define energy efficiency measures in buildings is not implemented in Poland [24]. No other studies conducted by Polish researchers provided more insights into defining nearly zero energy buildings on a national scale to the best of our knowledge [19]. More importantly, very few studies investigated the impact of subsidies on energy efficiency adoption in new construction and renovated households [8].

3.2. To what extent are the energy sources addressed in buildings energy efficiency studies in Poland?

Non-renewable energy sources, such as hard coal or natural gas, dominate the Polish energy market, especially for heating purposes, as shown in Ref. [25]. More than 40% of Polish households are connected to district heating [2]. Table 1 presents a breakdown of energy sources in Polish households [25]. As indicated in the Table, the dominant fuel remains hard coal in district heating systems, despite a slight decrease from 86.7% in 2011 to 81.6% in 2017 [26]. For heating purposes, coal holds 39% of the share of energy sources used to satisfy space and water heating demand, as shown in Fig. 3.

According to a study analyzing Polands' heating markets' current state, the existing energy grid is old [27]. It is subject to a low energy production efficiency and high level of pollutant emissions. Consequently, there is an urgent need for modernization that will include the assessment of transmission losses. District heating systems should also consider changing the users' demanded heat capacity to improve their efficiency [27]. Fortunately, in recent years, a transformation towards renewable energy is observed in Polands' district systems. The investment and maintenance of local heat sources and local heat distribution networks for residential buildings are undergoing [28].

On the building demand level, the study of Krawczyk (2016) [29] analyzed the gas used for heating in a Polish renovated household. The study provided energy conservation recommendations to meet the Polish energy efficiency law requirements of 2015 that the primary energy consumption factor is 120 kWh/m^{2}year. More interestingly, the study of Księżopolski et al. (2020) the potential of the changes of heat sources from coal to clean energy. The study investigated the impact of

Table 1
Energy consumption in households in Poland in by energy source and end-use in 2018 [25].

Energy commodity	Unit of measure	Total	Space heating	Water heating	Cooking	Lighting + electrical appliances
Electricity	GWh	29284	1305	2118	3168	22693
	TJ	105422	4698	7625	11405	81695
Heat	TJ	157000	107250	49750	x	x
Natural gas	TJ (GCV)	165679	88532	43892	33255	x
Solid fuels	thousands tons	10430	9365	935	130	x
	TJ10^3 t	267440	240132	23975	3333	x
Petroleum products	thousands tons	580	90	34	456	x
	TJ10^3 t	26440	3930	1534	20976	x
Of which:						
LPG	thousands tons	500	20	24	456	x
	TJ	23000	920	1104	20976	x
	10^3 t					
Heating oil	thousands of tons	80	70	10	x	x
	TJ	3440	3010	430	x	x
	10^3 t					
Energy from renewable sources	TJ	112675	98676	11784	2215	x
Of which:						
Solar energy	TJ	2129	106	2023	x	x
Solid biofuels excluding charcoal	TJ	108015	96800	9000	2215	x
Geothermal energy and ambient heat	TJ	2531	1770	761	x	x
Energy sources in total	TJ	834656	543218	138560	71184	81695

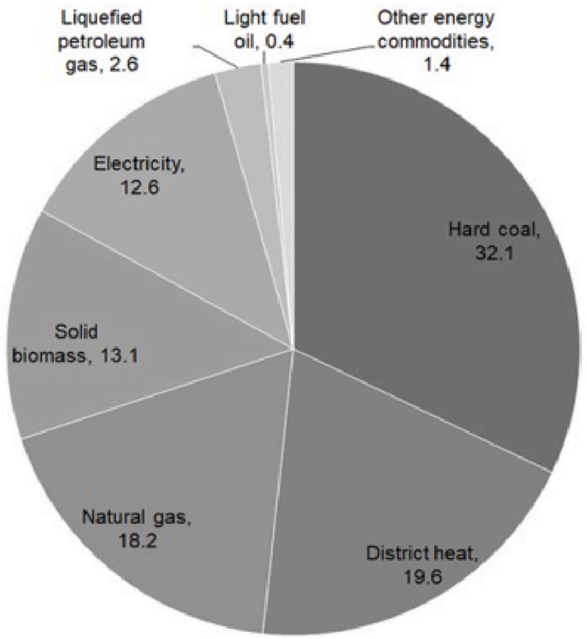

Fig. 3a. Structure of households energy consumption by various energy commodities in 2017 [25].

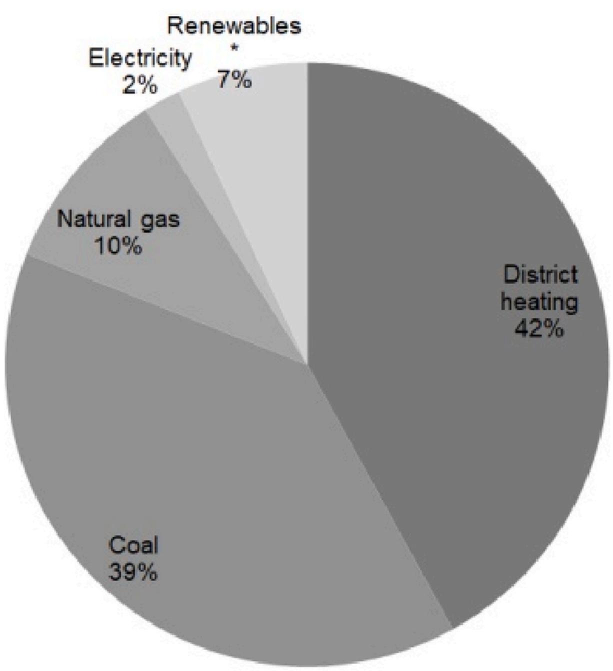

Fig. 3b. Share of energy sources used for heat demand in the residential sector in 2017 (* wood pellets, wood chips, biomass, firewood, geothermal, solar thermal) [26].

introducing heat source changes from coal boilers to gas, electricity, and heat pump/P.V. installations [8]. The study examined the potential for introducing new heat sources, including the zero-emission ones (P·V./heat pump installation) in rural Poland. According to Table 2, the conversion factor values of the primary energy calculation for solid fuels in Poland are low. Current primary energy factors used in calculations for different energy sources in households are given in the Regulation of the Minister of Infrastructure and Development of 18 March 2015 on the methodology of determining the energy performance of a building and

Table 2
Values for the non-renewable primary energy input factor for the production and delivery of an energy carrier or energy for technical systems "wi" [34].

No.	Method of supplying a building or part of a building in energy	Energy carrier type or energy type	wi
1	Local energy production in the building	Fuel oil	1,10
2		Natural gas	
3		Liquefied gas	
4		Hard coal	
5		Lignite (brown coal)	
6	District heating from cogeneration	Hard coal or natural gas	0,80
7		Biomass, biogas	0,15
8	District heating from a local heating plant	Hard coal	1,30
9		Natural gas or fuel oil	1,20
10	Electrical grid system	Electricity	3,00
11	Local renewable energy sources	Solar energy	0,00
12		Wind energy	
13		Geothermal energy	
14		Biomass	0,20
15		Biogas	0,50

*wi (the coefficient of expenditure of non-renewable primary energy for the production and delivery of an energy carrier or energy for technical systems).

energy performance certificates (Journal of Laws item 376). The study confirmed that without incentives, it would not be financially viable to abandon coal in households. The reviews above are samples of the few studies that addressed reducing carbon emissions for heat generation for buildings and substituting conventional energy sources by non–conventional sources, including renewables.

On the building supply level, Poland is facing a paradox of the domestic energy market. On the one hand, the share of local coal in electricity production is decreasing. Also, domestic hard coal mining is declining. On the other hand, however, the demand for imported hard coal remains high. According to the study of Zieleniec et al. (2020) [30], 10 million tons were imported last year from Russia, Chile, Colombia, the USA, and Kazakhstan. In addition, the importance of gas in the Polish energy mix continues to grow. Its share in 2018 approached 9 percent, and the demand is covered mainly with imported gas. Production of electricity from coal is falling; electricity imports are increasing; the importance of gas in the energy mix continues to grow, and renewable energy sources also play a more critical role in the system. These key conclusions confirm the stagnating trend in reducing greenhouse gas emissions [30]. In 2018, Polands' emissions remained at the 2017 level, exceeding 412 million tons of CO_2 equivalents, including nearly 150 million tons from the power sector alone.

The European Union can influence the Polish governments' directions regarding energy efficiency improvement and CO_2 emissions decrease. A study analyzed the European Union Emissions Trading Systems' impact on Polands' conventional energy sector in 2008–2020 and further till 2050 [31]. It found out that gas-fueled combined heat units and power units may be less affected by the EU cost regulation than hard coal-fired plants that may lose their profitability after 2020. However, the study underlines that Poland will not avoid deep decarbonization of the power sector to meet the post-Paris climate objective. The Polish government has also set up a plan: the 2030 Natural Environment Policy (PEP2030). This national plan includes measures to improve air quality by replacing old stoves and boilers or renovating the district heating network [32]. Public opinion and awareness regarding energy savings and energy efficiency will also have a major role to play. A study focused on the Polish energy sectors' readiness to be transformed noticed a shift in saving energy motivations [33]. It is no longer only related to money but to other issues such as environmental pollution, air quality, and global warming. People still tend to save electricity rather than heating, but the PEP2030 plans on promoting electricity as a heating source [32].

3.3. To what extent are policies and regulations addressed in buildings energy efficiency studies in Poland?

The earliest energy efficiency regulations in modern Poland date were developed after World War II. Formal needs in the field of permissible heat losses, expressed by the heat transfer coefficient, have been formulated in Poland since 1957 [35]. As shown in Fig. 4, the evolution of heat transfer requirements evolved remarkably in Poland. Earlier than many European countries, Polands' requirements for the heat transfer for walls were updated in 1964 before the oil crisis in 1972. The revised requirements of 1974 [36] and 1982 [37] were updated under the influence of the oil crisis [38]. According to Wójcik (2018) and up to 1985, the calculated energy usage of typical Polish buildings was 240–380 kWh/m^2 [35]. In the years 1991–1992, it was required not to exceed 160–200 kWh/m^2 (depending on the purpose of the building) [39], 1993–1997 it was 120–160 kWh/m^2 since 1998 it should be no more than 90–120 kWh/m^2 [40].

In 1994, the Polish Energy Conservation Agency (KAPE) was established as a legal entity under the Building Industry, Industry and Trade and Environmental Protection [42]. The KAPE formalized Poland's climatic zoning, which divides the country into five zones, as presented in Fig. 5 [41]. In 1996, a ministerial committee was created to identify the challenges of building energy efficiency and the utilization of renewable energy systems (RES). The fundamental construction law was amended in 1994 (Construction Law of July 7, 1994) [43]. With Poland joining the E.U. in 2004, the EPBD was adopted in 2009. Since 2009, a certificate of energy performance (EPC) is required for new buildings, and buildings are available for sale or rental. The calculation of the energy performance of a building is based on standard EN 13790 [44]. The energy performance certificates report the energy efficiency using the primary energy use intensity indicator.

The amendment to this regulation in 2013 introduced in Poland a gradual reduction of the heat transfer coefficient and the building's primary energy demand for heating, ventilation, and hot water for residential, public, utility, production, and storage buildings [41]. An obligation to insulate installation pipes and reduce solar radiation due to sun protection devices in the summer period was introduced. The provision on airtightness was maintained, allowing $n_{50} = 3.0\ h^{-1}$ for buildings with gravity ventilation and $n_{50} = 1.5\ h^{-1}$ with mechanical ventilation. Airtightness tests are only recommended. The energy performance requirements entered into force on January 1, 2014, and determined obligatory minimum requirements for new constructions and existing buildings. The calculation methodology reflects the building performance using the annual non-renewable primary energy demand (EP) index in kWh/(m^2/year), which is necessary to check minimum requirements [45]. Non-renewable primary energy factors are given in the regulation. The latest change introduced in 2020 suggests design process-related improvements, but not much for quality control [46]. Several updates (from 2015 [34], 2017 [47], and 2019 [19]) were introduced towards the nZEB target [48]. Table 3 summarizes the latest performance requirement that buildings must meet depending on their location [46].

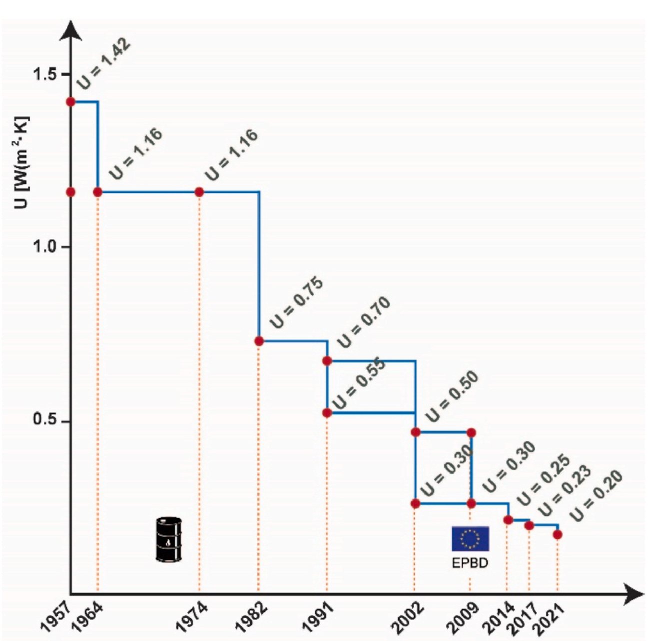

Fig. 4. Requirements for the heat transfer coefficient U for walls in force in Poland since 1957 [35,41].

In parallel to the evolution of building energy performance regulations, Poland enacted in 1998 a thermo-modernization law [35,49]. The Thermo-modernization Act of 1998 allows subsidizing the refurbishment of buildings from the state budget to reduce heat energy use [22]. Staniaszek and Firlag [20] distinguish three levels of thermo-modernization in Poland: (1) Low—modernization or replacement of heat source, (2) Medium—modernization or replacement of heat source together with window and door joinery or thermal insulation of the façade and (3) Deep—modernization of total replacement energy sources, the use of renewables or the use of high-efficiency cogeneration and envelope renovation. One of this law's main contributions is to replace coal-fired boilers and stoves with modern models and insulating walls.

Several publications were found in the literature that investigated compliance with the Polish EBPD requirements. The earliest study of Węglarz et al. (2011) proved that the Polish requirements for energy performance in new and retrofitted buildings are lower than those of other countries with similar climates [50]. Most of the studies focused on case studies with parametric simulations to explore different solution spaces coupled to carbon emissions, energy use intensity, or cost. Krawczyk (2016) [29] and Księżopolski et al. (2020) [8] investigated the impact of energy efficiency improvements in single-family houses. Firlag et al. (2018) [51] suggested a new definition for nZEB based on a case study renovation for three locations in Poland—Warsaw (medium climate), Szczecin (the warmest climate), and Suwałki (the coldest climate). The same author explored cost-effective measures for PEB [21]. Kwiatkowski et al. (2020) developed a different Energy Performance Certificate (EPC) or label for energy end-use of multifamily buildings in Poland [52]. The author suggested a new label for assessing buildings' energy performance to replace the primary energy indicator based on EN ISO 52016–1 [53]. All the reviewed studies for building energy performance calculation are considered as being complementary to existing regulation. Currently, the latest calculation methodology used in Poland addresses nZEB requirements in low Polish buildings.

3.4. To what extent are the building professionals' skills and education quality addressed in buildings energy efficiency studies in Poland?

Conditions in the Polish construction sector have changed considerably since the accession to the EU [54]. There is no data regarding the structure of the education of architects, engineering, and qualified personnel working in the construction sector. After the 1989 transformation, vocational education for building construction has been perceived as inferior to general education [55]. The Polish educational system was reformed in 1999 by creating a gymnasium, a 3-year course between primary and secondary school. As a result, young people's interest in vocational training dropped, and vocational schools' enrollment ratio fell [55]. In 2017, another educational reform closed all gymnasiums. The European Construction Sector Observatory (ESCO) noted that the number of students participating in VET training increased. Besides, the employment rate of VET graduates has risen to 82.1% [1]. A study that aimed to fill the knowledge gap regarding the returns to vocational education showed that VET graduates have, on

Zone	te [˚C]	te *) [˚C]
I	-16	7.7
II	-18	7.9
III	-20	7.6
IV	-22	6.9
V	-24	5.5

te – outside design temp. [˚C]
te *) average annual outside temp. [˚C]

Fig. 5. Design temperatures of the outside air for Poland [41].

Table 3
Maximal E.P. for heating, ventilation, and DHW preparation according to the regulation of the Minister of Development (September 16, 2020).

Type of building	Maximal EP for the heating, ventilation, and domestic hot water preparation (kWh/m^2·year)
Residential:	
Single-family	70
Multifamily	65
Collective residence building	75
Farm	70

average, a higher probability of finding a permanent job [55]. This study also found out that secondary-vocational education graduates have a higher wage than secondary general education graduates. However, the wages of vocational education graduates remain lower than those of general education.

Despite students' growing interesting VET training, the Polish educational system still has challenges to overcome. The qualification of employees of the construction industry in the RES and energy efficiency sectors need to improve. This improvement will necessarily require the standardization and expansion of curriculums [56]. The study of Więcka et al., conducted in 2013, developed a strategy for improving employees' qualifications in the construction industry in renewable energy sources (RES) technologies and activities enhancing the energy efficiency of buildings. The study presented a status quo analysis on qualified personnel working in construction.

Moreover, the European Union's accession in 2004 has profoundly impacted patterns of Polish labor migration. The estimated demand for qualified personnel in the sector of energy efficiency in the construction industry is high. According to the ESCO study, it is estimated that yearly, around 13,000 Polish VET and engineers are migrating outside Poland since 2000 [57].

3.5. *To what extent is indoor environmental quality addressed in buildings' energy efficiency studies in Poland?*

The Polish national calculation methodology for building performance is based on five overarching EPB standards ISO 52000–1, 52003–1, 52010–1, 52016–1, and 52018–1. ISO 52016–1 provides the procedures to calculate the internal temperatures and energy needs for heating and cooling, including thermal insulation, airtightness and ventilation, the building mass, solar heat load, and passive solar energy and internal heat gains for buildings [53]. In the Polish national regulation, there is only one sentence mentioning thermal comfort. The regulation states that " *overheating should be avoided during summer periods*". There is also the requirement about windows glazing being able to block some part of the irradiation. However, there is nothing more specific about thermal comfort or overheating calculation in the Polish regulation, which means that the Polish standard complies with EPB standards default recommendations. Although EPBD states that minimum energy performance requirements shall take into account indoor climate conditions, the Polish regulation neglects indoor environmental issues while enforces energy conservation measures.

Few studies addressed thermal comfort in Polish residential buildings. The study of Węglarz et al. (2011) focused on optimizing small residential buildings' thermal characteristics [50]. The study focused on designing the building characteristics to maximize comfort and minimize costs. It recommends a walls insulation thickness of 25 cm, a roof insulation thickness of 35 cm with rock wool and extruded polystyrene. It also recommends using a mechanical ventilation system with heat recovery of annual energy efficiency equal to 75%. In 2017, Ferdyn-Grygierek et al. [58] conducted an automated optimization for building thermal design using genetic algorithms. The states that using large windows can reduce heating demand allow using solar heat gains in winter. However, blinds should be added for the summer period. It also found out that when considering both life cycle costs and thermal comfort, the optimal insulation thickness is higher than the minimum requirement.

Moreover, the study of Fedorczak-Cisak et al. (2018) found out that applying only the Polish regulation's energy efficiency requirements does not assure comfort in nZEBs [59,60]. The paper recommended updating the national calculation methodology to include minimum requirements for solar protection. In the same year, Fedorczak-Cisak published another study that conducted a thermal diagnostic of natural ventilation in an old multifamily building [61]. It states that using large windows can reduce heating demand: it allows using solar heat gains in winter. However, blinds should be added for the summer period. It also found out that when considering both life cycle costs and thermal comfort, the optimal insulation thickness is higher than the minimum requirement.

A recent study conducted by Kozielska et al. (2020) [62] investigated indoor air quality in residential buildings in Upper Silesia, Poland, during the winter season. The study monitored two existing flats and four houses without any linkage to the monitored households' energy efficiency characterization. Another study by Piasecki et al., 2020 [63] suggested an indoor environmental quality indicator to assess retrofitted historic masonry buildings. The study relied on universal standards, including ISO 7730 and EN 13187, without specific linkage to the national EPB standards.

3.6. *To what extent are advanced building envelope and active technologies addressed in Poland's energy efficiency studies?*

The building energy conservation policies in Poland evolved significantly during the last two decades. The study of Życzyńska et al. (2015) documented the evolution of the U-value of envelope components between 1974 and 2021, as an example of those policies' progressive nature [38]. The paper of Wójcik et al. (2017) focused on the renovation of existing buildings with historical façades [64]. The authors tested Autoclaved Aerated Concrete (AAC) as an internal insulation material for better heat and moisture control. The study of Grygierek et al. (2018) presented a methodology for the optimal selection of the envelope parameters for a single-family house with natural ventilation [65]. The study focused on the cost-optimality of the envelope solutions, including insulation and airtightness, without addressing the nZEB target or evaluating advanced envelope technologies. Węglarz et al. (2018) investigated three construction technologies (conventional construction, wooden frame building, and straw bale) of the same building in a 40-year long life cycle [66]. They used the life cycle assessment method to compare the cumulative energy and embodied carbon for the three variants. Despite having a higher energy use during the operation stage, the straw-bale technology had the best results and appeared to be the more ecological solution. The paper of Kisilewicz et al. (2019) assessed the way active insulation systems can replace standard passive insulation in walls [67]. It used a concrete layer in the external wall having a pipes system where a refrigerant circulates. An average of 63% could reduce the heat losses through the external walls. This system can be used in both new and existing buildings. However, such a system should be turned off during the summer to favor the external wall's natural cooling.

Despite the energy efficiency policies and the thermo-modernization programs and renovation actions the construction quality of most newly constructed and renovated energy-efficient building envelopes remains mediocre [68,69]. Our observations and discussions with experts indicate the presence of systematic thermal bridges that cause heat loss through inconsistent breaks in the thermal envelope. Common culprits include elements that penetrate the thermal envelope to include windows and doors, wall ties, structural beams, pipes and cables, and cantilevers [70]. Among the most used building envelope constructions systems External Thermal Insulation Construction System (ETICS) in walls or steel sheet roofs emerge as the most dominant construction system. Despite the advantages of ETICS their placement and their insulation thickness (high conductivity) remain problematic and results in pseudo insulation [71]. Moreover, assuring airtightness of envelopes through blower door tests is not a common practice.

On the other hand, the evolution of energy-efficient HVAC systems sales in Poland is proven and is going slow. Boilers are very commonly used in the Polish residential building stock, as shown in Fig. 5. During the last ten years, gas boilers took over the solid fuel boilers. Slightly electric boilers' sales are increasing too.

Fig. 6 presents only an indicative picture of heating systems sales in a sector dominated by district heating. A District heating system is commonly used in the Polish residential building stock. In 2019, there were 412 district heating systems in Poland, representing 54.912 MWth of capacity [26]. An article investigated the expected future trends of the development of the Polish district system [73]. It highlights that the European policy will eventually make the energy demand from such a system decrease. However, in the short term, the Polish district system is still expected to develop. It will have to be modernized with a change of fuel, and the examined possibilities (biomass combustion, cogeneration) still have challenges to overcome.

Regarding DHW consumption, few studies investigated the efficiency of DHW in Poland [74]. According to Bertelsen et al., the average energy use for DHW in Poland is 2600 kWh/year per household [7]. Chmielewska investigated 626 apartments in 2 years to determining DHW energy use in multi-apartment buildings [75]. In another study, Cholewa et al. analyzed nine multifamily buildings over 20 years [76]. The study aimed to propose methods to reduce the energy used in DHW systems in old buildings. It found that in existing buildings, 56.7%–70.5% of the heat used in DHW systems is due to heat losses.

Another system that is becoming more popular in Poland is the heat pump. Heat pumps are mainly used for DHW and rarely used for space heating [77]. Between 2011 and 2020, the sales of heat pump almost quintupled (see Fig. 6). Lower heat transfer coefficient and EP values in the Polish EPB regulations call for smaller capacity heating devices. Hence, the heat pump market is expected to develop in the country. In 2014, Flaga-Maryanczyk et al. experimentally tested a ground-source heat-exchanger for PH-certified single-family houses [78]. The study proved that the ground-source heat exchanger coupled to the mechanical ventilation system successfully suppressed the outside air

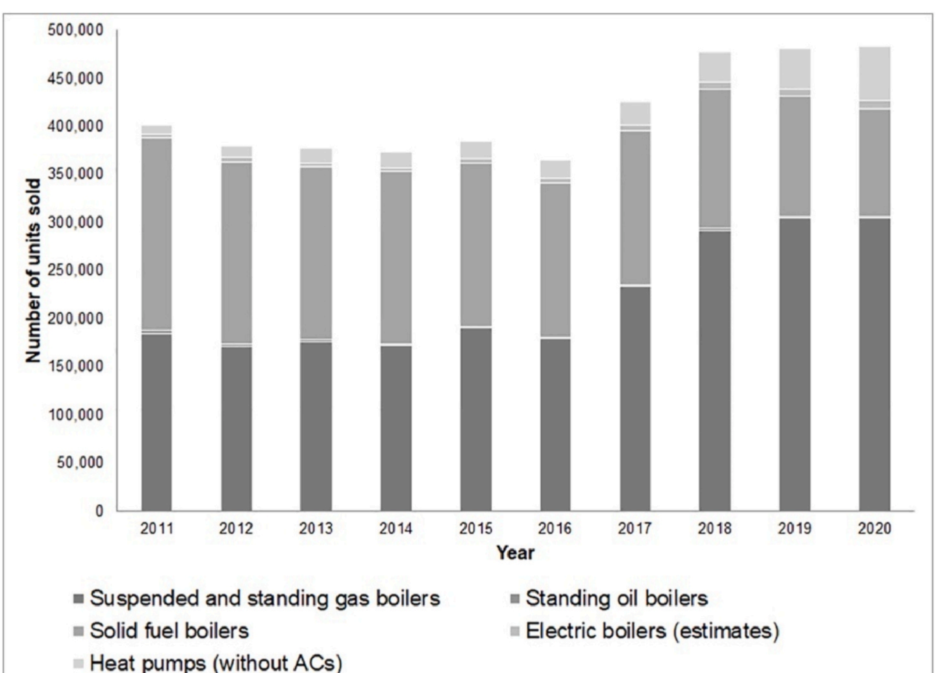

Fig. 6. Sales of boilers and heat pumps (without AC) in 2011–2020 [72].

temperature fluctuations, which was significant, especially during the severe frost in early February. The study of Nems et al. (2018) analyzed air and ground source heat pumps in Polish conditions [79]. It found out that operating a ground source heat pump combined with an existing heating system (coal-fired boiler) could make annual profits reach 62% (32% for an air source heat pump). However, the study considers a greenhouse and not a residential house.

To neutrally run heat pumps, PV panels could be coupled to the system. This possibility was investigated by Romańska-Zapala et al. (2017) [80], who considered a low-energy single-family building in Poland during winter, using PV systems with or without batteries. The use of a PV system in winter is not recommended because of the low solar irradiation and the low energy gain. Only 175 kWh of primary energy could be saved with a PV system having batteries compared to a PV system without them. The issue is that the real energy savings can only be shown if the whole year is studied. A pipe ground-air heat exchanger (GAHE) can also cooperate with an air handling unit to cool a summer building. A paper studied this possibility measuring the system's operating parameters in two cases: with or without GAHE [81]. It found out that using a GAHE allows pre-adjusting the supply air temperature by pre-heating or pre-cooling, which reduces the energy inputs. The maximum energy efficiency can be achieved if the system can select its fresh air source depending on the conditions and requirements, which vary for different occupancy schedules or different rooms.

To summarize, in the last few years, the tendencies of sales of HVAC and renewable energy systems indicate that heat pumps and solar collectors have known a significant increase. According to the information of the representative of the Polish Ministry responsible for construction, provided on October 6, 2021, during the 20th Thermomodernization Forum, residual energy requirements that need to be covered by renewable energy in the housing construction equal approximately 50 kWh/m^2/a [82]. This might be further encouraged by introducing dynamic pricing tariffs for electricity in Poland [83]. Grid flexibility and prosumers models of dynamic pricing need to be developed [84]. Fig. 7 shows the percentages of the variation of heating devices and solar panels in Poland between 2011 and 2020.

Our review's last item investigated the status of mechanical ventilation systems and heat recovery units in Polish residential households. Poland has declared that from 2021 all newly built buildings shall be nZEB. Mechanical ventilation systems remain a novel aspect in the Polish residential sector. Integrating the central mechanical ventilation system with heat recovery in the existing buildings remains challenging [85]. Therefore, there are many approaches to adopt hybrid or decentralized systems [86]. Sowa et al. studied the application of a humidity-sensitive demand-controlled ventilation system in an 8-floor multi-unit residential building for Warsaw's climate [87]. Two versions of the humidity-sensitive demand-controlled ventilation were analyzed. The article underlines that gravitational ventilation is often unsatisfactory: lower floors are excessively ventilated, and higher floors have a smaller airflow, which increases energy demand in both winter and summer. According to Ratajczak et al., mechanical ventilation is not popular in Poland because it is sophisticated [86]. The awareness about the hygienic ventilation, thermal efficiency of the D system of the EPBD requirements, acoustic noise of fans, and cost contribute to low market uptake.3.7.

To what extent is the outdoor air quality addressed in Poland's energy efficiency studies?

Poland has the most acute ambient air pollution among EU member states due to the use of solid fuel [88]. The use of solid fuel (e.g. coal and wood) for heating in the housing sector is common in social housing and is associated with fuel poverty [89]. During winters the outdoor air quality and consequently indoor air quality is poor due to solid fuel combustion. Since the year, 2018 there has been a significant improvement to meet air-quality standards at the level of local urban and regional authorities [90]. The amendment to national law (2017) allowed local authorities to establish anti-smog regional restrictions in domestic solid-fuel combustion for heating purposes [91]. The health effects and risks associated with occupational exposure to outdoor polluted air in urban areas in Poland harm the health of building residents [62,92]. Poor air quality has been shown to increase the risk of asthma and well-being [93].

In 2019, the Polish Building Energy Standard adopted the EN-16798-1 standard requirements and the [94]. The standard recommends specific criteria for CO_2 concentrations in living rooms and bedrooms that exceed outdoor levels. Table 4 presents the categories for indoor environment quality and the expected levels of these. However, the EN 16798 standard does not address outdoor air pollutants and assumes low levels of outdoor air pollutants. Despite the initiatives to ban solid fuel use in Cracow and Upper Silesia, the Polish building standard allows the use of solid fuels and is mainly focused on reducing the indoor emissions

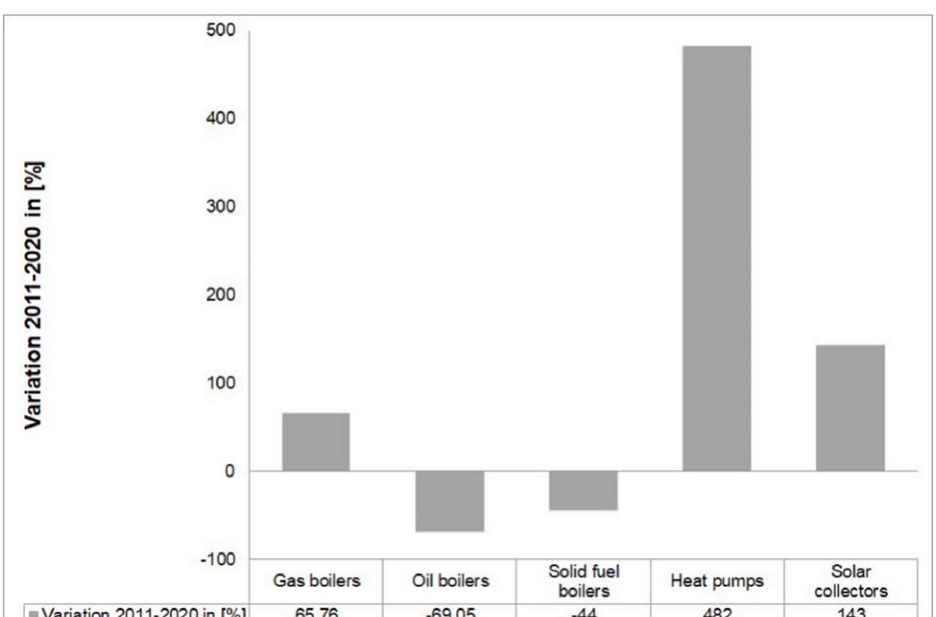

Fig. 7. Variation of heating devices and solar panels sales in Poland between 2011 and 2020, expressed in percentage based on [72].

Table 4
Indoor environment quality (IEQ) categories and corresponding CO2 concentrations in occupied living rooms and bedrooms [94, p. 167].

IEQ category	Level of expectation	Designed ΔCO_2 concentration (ppm above outdoor) for	
		living rooms	bedrooms
I	High	<550	<380
II	Medium	550–800	380–550
III	Moderate	800–1350	550–950
IV	Low	>1350	>950

of solid fuel boilers.

In this context, Poland is facing another transition to remove pollutants from its outdoor urban environments and reduce the exposure of citizens in the most polluted areas [92]. The Polish building standard does not address indoor and outdoor air quality in parallel. Because the transition to natural gas, geothermal heating, district heating, and other low carbon heating such as heat pumps and renewable energy will adversely affect the inhabitants already vulnerable to fuel poverty. Fuel poverty vulnerability for low-income households impedes the standardization committee to ban solid fuel due to the increased costs [88]. Financial support from the national government and EU to address this problem is needed to ensure the transition from solid-fuel heating to clean heating technologies.

4. Focus group discussions

The focus group discussions were conducted by doing in-depth discussions with Polish experts. The meetings provided insights into the energy efficiency landscape of Polish residential buildings. They provide a better understanding of the current and future challenges of Poland's building sector's energy transition. The main findings of the focus group discussions are grouped under a SWOT analysis in Table 5.

4.1. Strengths

The Polish government identified increased energy efficiency as one of its priorities in its long-term energy policy. Poland has had an old tradition of developing ambitious and consistent energy efficiency regulations for building since 1957 [35]. The Polish building regulations are adopting the EPBD requirements and getting closer to the EU 2030 and 2050 carbon targets. The government recently reconsidered its position on coal phase-out and agreed to accelerate it and to shut down coal mines by 2049 progressively.

In parallel, there is a strong demand for housing in Poland combined with a high construction speed and good quality workers. 60–100 thousand new buildings are constructed every year [2]. Workers often travel around the world and come back to Poland as new owners with an international experience. The FGD revealed a comeback to technical schools and vocational training (see Table 5). Consequently, progress in construction quality can be observed during the last twenty years. Moreover, Poland has diverse funding programs and access to commercial financing. The thermo-modernization program and existing incentives are stimulating the market towards renovation.

Finally, Poland has a robust industrial landscape of companies that efficiently supply building envelops technologies, HVAC systems, and RES. There is increasing awareness about energy efficiency and the know-how of building professionals can increase investors' interest and courage. The liberalization of the energy market and the most vulnerable support can catalyze the investment in building energy efficiency. The national plan for 2030 is focused on renovating the district heating network in urban households [32]. According to data provided by the Central Statistical Office of Poland, a significant share of urban households is connected to district heating networks (nearly 60%) [2]. Together with the systematic replacement of old stoves and boilers, Poland can tackle the coupled problems of air quality and energy efficiency in its residential sector.

Table 5
SWOT analysis for improving energy efficiency in the Polish residential building stock based on FGD.

SWOT Analysis for improving energy efficiency in the residential sector	
Strengths	**Weaknesses**
• Strong demand for housing ownership and high construction rates • Highly skilled labor that comes back to Poland with international experience • Interest in technical education & vocational training • Most Polish residential buildings are renovated • Financial support from the state • Progress of construction quality and projects delivery process • A long history of consistent EE regulations • Partial implementation of EU EPBD requirements • Increasing awareness about EE • The proliferation of district heating grids	• Weak financial and institutional capacity • Centralized governance politicized and over-empowered ministers • Pseudo EPCs • No measurement of energy use and lack of enforced energy audits • Mechanical ventilation is not elaborated in regulations and practice • Lack of adoption of the EPBD cost-optimality approach in current regulations • Lack of high-quality control during the permit process (design and construction reviews) • No carbon taxation • Intense lobbying of real estate investors and land developers against EE
Opportunities	**Threats**
• Clean air projects to eradicate fuel poverty and assure air quality • Emigrants and cross-border construction workers travel abroad, see, learn, and then come back. • Scandinavia, France, and Germany significantly influence Polish construction sector practices (vapor breaks, airtightness, ETICS, etc.). • Increasing local demand for good quality insulation and heating systems • Increased awareness about liability and the role of legal claims to assure construction quality and performance • Increasing prices of fossil energy and operating expenses of inefficient buildings • The proliferation of on-site renewable energy systems, including solar and geothermal systems • The significant potential of geothermal energy	• The strong lobby of fossil energy companies to promote energy dependence and discourage autonomy (including the investment in nuclear energy) • Globalization of the coal market resulting in cheap coal and a decrease in fossil fuel prices • Investment in district heating to improve air quality in buildings while abandoning EE in buildings • Switch from fuel poverty to overheating problems • Insufficient anti-smog measures in cities (poor outdoor air quality), & continue burning coal in domestic stoves. A demand that surpasses the availability of building materials and systems • High cost of construction materials and systems • Occupant behavior (e.g., wearing shorts during winter) • Abandoning EPBD requirements and the Emissions Trading System • Continuous immigration of skilled labor

4.2. Weaknesses

The primary energy source in Polish households is coal. Electricity generation is coal-based, and the existing electric grid is old. Winter pollution in Poland is mainly caused by the burning of solid fuels in primitive and inefficient household heating appliances. Without addressing air quality improvement in Poland, any energy efficiency initiative or law will be hardly effective. Consequently, building energy policies should be coupled with financial support programs to target air quality improvement and eradicate fuel poverty.

In this context, Poland should accelerate the reinforcement and consolidation of its technical and institutional capacity. The government's energy efficiency strategy progress has been slow. Also, there is a need to develop a framework for nZEB in Poland. The current Polish energy efficiency target for domestic hot water (DHW), ventilation, and heating in a single-family house, the primary energy requirement is set at 70 kWh/m^2·a. However, the primary energy demand targets are impossible to fulfill with natural ventilation only. The current standards do not specify that mechanical ventilation has to be used. As a result, developers try to manipulate the air volume change calculations and use low-quality mechanical systems with very low flow rates. Also, the cost-optimality approach that should define the performance targets of the Polish EPB is not implemented. Moreover, cooling peaks that can occur 15–20 days a year are not addressed in the EPB calculation method. There is no overheating calculation method in the Polish EPB method, and solar protection is only recommended prescriptively.

Moreover, there is a lack of focus on inspection and verification. According to the FGD, one of the weaknesses of the Polish institutions is centralized governance. Centralized governance does not empower local authorities to implement and verify many energy efficiency policy requirements. For example, the implementation process of EPCs does not ensure inspections of passive and active energy conservation measures. Energy efficiency liability and liability insurance are new concepts in Poland, where third-party companies can assure construction quality and performance efficiency. The Polish housing market is not standardized enough to integrate quality control and inspection for energy efficiency measures. As shown in Fig. 8, there are no design reviews or construction quality assurance for high-performance households, including airtightness and ventilation.

Also, the decisions about energy efficiency mechanisms and targets are sometimes politicized, and some ministers without technical backgrounds adopt ineffective measures or policies. For example, the current EPC scheme is inefficient. The FGD revealed that the current Energy Performance Certificate (EPC) scheme is weak. Unlike in many countries (ex. Finland, Belgium), no energy classes were implemented in Poland. There is no rating scale (A-G), the certification is valid for ten years, and it is not mandatory. The certification requires proving that the certified building has a primary energy demand not higher than the reference one. The certificate contains only basic data about the building - location, useable area, date of construction, type of heating, ventilation, and hot water system. The values of primary, final and useful energy are also calculated. Since 2015, the building elements and their heat transfer coefficient are also described, and the efficiency of the heating, ventilation, and hot water systems. Currently, energy performance certificates are required for public and private buildings. However, EPC can be waived for private ownership transfers if the buyer and seller agree. This condition is a primary reason that hinders the proliferation of EPCs in Poland.

Therefore, it is essential to strengthening the EPC schemes, include carbon emissions indicators, enforce inspection and develop a guiding design framework and recommendations for nZEB.

4.3. Opportunities

Polish construction experts and real estate developers think that sustainable construction will continue to develop on a massive scale and become profitable. The market will continue to grow under EPBD targets to reach zero carbon buildings. The government also develops projects to eradicate fuel poverty and improve thermal insulation, such as the 'Clean air' project. In this context, Poland has a high potential to target European funding to prepare for a new generation of low carbon buildings, especially if the air quality improvement funding is coupled with deep renovation.

In addition, the increase in energy prices is a real opportunity for energy efficiency in Poland. It can encourage households to adopt energy efficiency measures and self-invest. The cost-optimality approach defines by the EPBD can promote the adoption of energy efficiency measures and actions. As the coal phase-out is bound to happen, renewable sources appear in Poland with increasing popularity. Geothermal energy would be a reliable energy source at a local scale: 80% of Poland's area has the right geothermal conditions [95]. Some regions, like the Tatra Mountains region, use it for district heating purposes. In many places, the use of geothermal energy has not started despite its potential. Besides, agricultural areas with plants and animal wastes can use biogas, and forest areas dispose of with biomass. The number of solar plants is also increasing across the territory. Wind energy is not as popular, but the number of wind stations will increase, as the legislation gave opportunities to install new ones. In January 2020, the Polish Ministry of Climate published a draft act on offshore wind energy [96]. It is planned to build farms with a total capacity of 8–10 GW.

Moreover, Polish emigrants and skilled labor living abroad can be part of the Polish energy transitions adopting advanced efficiency technologies such as vapor breaks, airtightness measures, and heat pumps. They learn new techniques, strengthen their skills and acquire knowledge before coming back to Poland. Constructors and workers are also more informed about legal claims. Consequently, the construction quality and expertise are improving. More importantly, the demand for good quality insulation and heating systems is also increasing. The Polish timber market is developing slowly, and it can offer an opportunity for cost-effect nZEB.

4.4. Threats

Poland is working towards reducing its dependence on coal and forging ahead with plans to produce nuclear energy. The Polityka Energetczna Polski (PEP) strategy is set to begin in 2026, includes the construction of six reactors in two locations. According to the plan, the first reactor will begin operation in 2033, and all six should be up and running by 2043. Paradoxically, nuclear energy, which is "clean" in terms of CO_2 emissions, will slow down energy efficiency improvement even further. If Polish CO_2 emissions fall because of the nuclear power

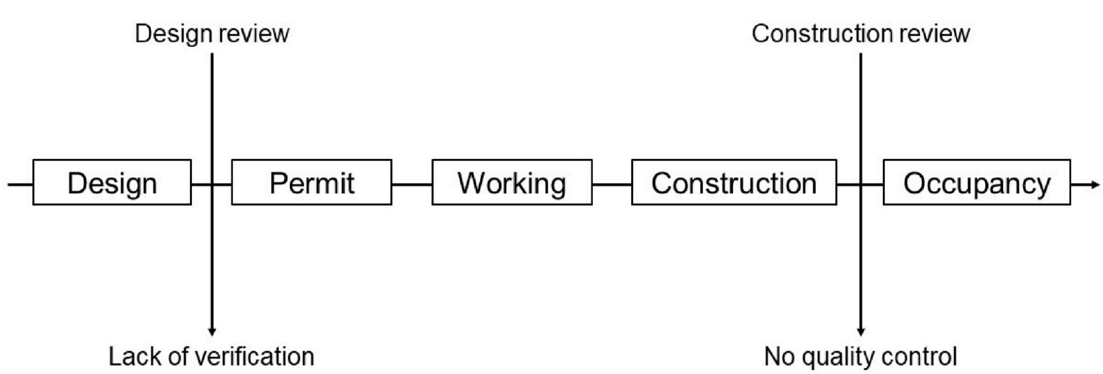

Fig. 8. Lack of quality control and inspection during the permit process.

plants, there will be less pressure to decarbonize the building stock. Moreover, nuclear energy investment will strengthen the energy lobby and promote dependence and discourage autonomy, making the nZEB targets obsolete. Like the centralized approach of nuclear energy production, the excessive investment in district heating in urban areas can slow down buildings' energy efficiency.

The globalization impact of the coal and natural gas market prices can be another threat. Poland imports coal from Russia, New Zealand, Chile, or South Africa and imports gas from Russia, the USA, Norway, and Qatar. If the gas and coal imports are cheaper than local coal, energy efficiency will be delayed. The energy transition in Poland will remain important during the next 30 years. The Polish government is willing to promote energy efficiency and raise energy performance requirements in buildings. However, the intense lobbying of energy companies and real estate developers might threaten the progress of energy efficiency in residential buildings.

Another threat can be missing on the consolidation of Polish policymakers' human capacity, building professionals, and building occupants. If the current EPC scheme remains flawed and the promotion of RES is becoming a priority. Energy efficiency can slide to be a second priority. Also, occupants' rebound effect can even threaten developing energy efficiency in the Polish residential building stock. People tend to wear shorts during winter. Hence, for a long time, the focus of building developers has been on heating. But thermal and spatial adaptation [97] are not addressed in energy efficiency schemes.

Finally, as the wood market is developing across Europe, the demand for timber construction is growing to achieve low carbon houses. There is a marginal presence of timber construction in Poland. The development of the wood market in Poland is slow despite its cost-effectiveness [98]. People view brick as a better material as it is more robust and fireproof. Hence, wood is instead developed for roofs and not walls. In 2017, the Ministry of the Environment created the 'Polish Wooden House' forum – to live in harmony with nature [99]. Between 2018 and 2022, 11,000 multifamily flats and 950 single-family houses should have been constructed. Although three years have passed, the project has not been implemented to a satisfactory extent. Not paying attention to the potential and benefits of timber construction can threaten the proliferation of nZEB.

5. Discussion

The following section discusses the outcomes of the literature review and the focus group discussions. The findings and recommendations that can be extracted from the results are presented in the following paragraph. The strengths and limitations of the study and its implications on practice and future research are also discussed.

Poland is facing many challenges for its transitions to being highly efficient and decarbonized by 2050. The SWOT analysis revealed numerous threats that require the EU to continue to support Poland. Currently, the housing sector is responsible for 75% of CO_2 emissions in Poland for power and heat generation [100]. On one side, develop a low carbon energy mix and infrastructure, and on the other side achieve an energy-efficient building stock. Outdoor and indoor air quality and the out phasing solid fuel remains a prerequisite during this development to assure smog-free cities. Visiting large cities such as Krakow, Wroclaw, Poznan, Katowice, Lodz, Warsaw during winter indicates the importance of couple any future energy efficiency measures to air quality. Simultaneously, high urbanization rates are increasing the demand for housing in cities and suburban areas. In the context of this interwoven reality, progress is expected to be slow.

Moreover, the FGD revealed that not many PH and nZEB exist in Poland due to two main factors: knowledge and cost. The general perception about PH is that they are challenging to implement and expensive. Low and middle-income self-builders have no experience with PH's technical requirements regarding glazing surface and orientation, external solar protection, thermal bridges, cooling design, shading control, and geometry complexity and compactness. Simultaneously, new housing owners prefer smaller houses for affordable cost because a smaller surface area allows them to have lower taxes. In Poland, the tax is 8% for a floor surface of 200 m^2 and goes up to 23% for a floor surface greater than 200 m^2.

Consequently, the introduction of mechanical ventilation systems, heat exchangers, or renewable systems results in a remarkable increase in the total building price. In this context, Poland should work on developing a framework to guide the policy heating decarburization towards Zero Carbon Buildings [101]. Finally, the following paragraphs gather the main findings of the study.

5.1. Findings and recommendations

1. Poland is transforming from a carbon-intensive housing sector to a low emission building sector. This transition is slow, but the policy landscape is driving the country on the right track. For example, residual energy requirements that need to be covered by renewable energy in the housing construction equal approximately 50 kWh/m^2/a [82]. By 2050, 65% of existing buildings must achieve the EP index of no more than 50 kWh/m^2/a, and 22% from 50 to 90 kWh/m^2/a. The remaining 13% of buildings, which due to technical or economic reasons cannot be modernized so deeply, will achieve the EP index in the range of 90–150 kWh/m^2/a [82]. Despite the substantial demand for energy efficiency, renewable energy is competing with energy efficiency in residential buildings, and preparedness for ensuring nZEB and NZEB is currently low.
2. Poland has a very diverse and rich technology and energy market, but its main problem is financial accessibility. Building technologies and systems towards nZEB are expensive and require highly skilled building professionals. The EPBD cost optimality approach is applied in the Polish regulations resulting in competing interests between investing and encouraging E.E. vs. RES. 3. Poland has highly skilled labor of building construction professionals, but they are not encouraged to operate in Poland.
4. Two major archetypes dominate the Polish residential building stock: (1) Multifamily houses in urban areas and (2) single-family dwellings in rural and low-density areas [102]. The houses are heating-dominated, and the building stock is not well insulated. It is estimated that more than 70% of detached single-family houses in Poland (3.6 million) have no, or inadequate, thermal insulation [20]. The average energy use intensity in old buildings in Poland is 175 kWh/m^2 per year. Heating comprises more than 75% of all energy use, including DHW, cooling, lighting, and appliances. Heating and electricity energy remain associated with high particulate pollution (SO_2, NO_x, $PM_{10,}$ and $PM_{2.5}$) and CO_2 emissions problems due to coal-fired boilers (including biomass and waste).
5. Indoor environmental quality in Polish households requires more attention. The influence of the soviet epoch on thermal comfort perception and thermal adaptation can threaten the expected energy use reduction [97]. Also, the introduction of mechanical ventilation and indoor air quality requirements must be further adopted in regulations and practice. Compliance with EN 16798 for ventilation and room conditioning systems (Modules M5-1, M5-4) must be enforced [94].
6. There is a lack of a multicriteria environmental impact approach during the whole life cycle of products and solutions. LCA and Environmental Product Declarations (EPD) will be essential to decrease buildings' embodied carbon [103]. The Polish academic and professional building experts need to be trained as soon as possible to be prepared for the EU's newly introduced carbon tax for operational and embodied energy-associated emissions that will be required around 2025.
7. There is a lack of human capacity and human infrastructure in Poland, including local authority officials, building professionals, and industrial stakeholders. The lack of capacity building for energy-

efficient buildings will affect any implementation plan. Accredited training programs are required for construction craftsmen (women) and site workers. Setting up the qualification and providing training and continuous education for middle and senior-level professionals on energy efficiency and use of RES in building projects must be achieved. Among many professionals and building owners, there is confusion about the priority of (1) reducing the demand for energy and implementing energy conservation measures (ECMs), compared to the (2) use of sustainable sources of energy instead of finite fossil fuels or the (3) use of clean fossil energy as efficiently as possible.

Based on these findings, we propose the Polish governments should:

- Invest in human capital education and local know-how development. The investment should go hand in hand with strengthening governance and research institutions, and education bodies. The Polish aims to increase research and development expenditure to 2.5% of GDP by 2030 still needs to be complemented by concrete measures [5]. The cohesion funds for the energy security of the Visegrad countries can be a major source of funding for the renovation of the neglected and energy inefficient building stock in Poland, the Czech Republic, Slovakia, and Hungary [104]. For example, Poland and the Visegrad countries can create an observatory of high-performance buildings that promotes excellence and initiatives in the construction sector towards nZEB. The transition of the building sector in the Visegrad countries to nZEB standards can be approached through this political alliance [105].
- Revise the national building energy performance calculation method to comply with the EU EPBD cost-optimality method [24]. The cost-efficiency of energy performance requirements must be assessed by calculating the life cycle costs for the building and building elements based on different packages of measures applied to a reference building and setting them concerning both the energy use and CO_2 emissions. Poland participated in the EU-funded TABULA and EPISCOPE projects to develop national building typologies representing the residential building stock [11]. The Polish building stock is classified based on four archetypes namely: Single-family houses, terrace houses, multi-family houses, apartment blocks. The classification groups buildings according to their vintage based on the dates of introducing new building envelope requirements for U-values. The classification clusters buildings for the periods: before 1945, 1946–1957,1958-1982,1983–1991, 1992–2002, 2002–2009, 2010–2013, 2014–2016, 2017–2020, and since 2021. The use of the existing reference buildings as a baseline will enhance the Polish national building performance calculation method to become accurate, reliable [106], and ready for any future carbon emissions taxation scenarios within ETS pricing of greenhouse gases [107].
- Prioritize air quality and energy efficiency measures and actions and increase nZEB, hand in hand with heating and cooling decarbonization, to make buildings compatible with the EU EPBD 2050 vision. The promotion of cleaner heating for energy-poor households and air-polluted neighborhoods should be priority number 1 in any energy efficiency legislation.
- Lead to legislative proposals by continuously reviewing the EPBD and implanting the Cost-Optimality method. A harmonized ecosystem of laws, regulations, and technical guides should be created to guide the transition towards energy-neutral and carbon-neutral buildings. According to the Polish National Energy Conservation Agency (NAPE), the emission threshold for new buildings is expected to be 0 kg of $CO_2/m^2/a$ in 2050. However, there are no assumptions for the carbon emission threshold in 2030, but from the calculations made with the assumption of the energy mix in 2030, it will amount to about 5 kg $CO_2/m^2/a$ [110]. Based on the expert discussions and the Polish Green Building Council 2050 roadmap to decarbonize the construction sector, we suggest redefining the nZEB requirements in the Polish national plan considering four main parameters [108]:
  - o The energy performance of the building expressed in primary energy used,
  - o The share of energy requirements supplied from renewable sources including biomass produced on-site or nearby and,
  - o The carbon emissions are associated with operational energy use.
  - o Create an annual reporting system for construction cost and building technologies cost in Poland to consolidated existing platforms [109].

Table 6, summarizes the suggested building performance requirements taking into account the EU cost-optimality approach and carbon tax (pricing) approach to create environmental benchmarks for buildings [15,111].

- Revise the current EPC scheme that is flawed and continue vigorous enforcement of EPBD implementation. For example, rented homes should achieve EPC D by 2030 and all homes for sale should meet the EPC C by 2030. Also, Poland has to enable the upcoming Smart Readiness Indicator (SRI) and develop its method for in-use smart performance and quantitative assessment. The national EPC framework needs major revisions to ensure coherence with all EPBD instruments including Digital Building Logbooks, Renovation Roadmaps & Passports, Level(s) …). This will nurture the EPC database's existing record and allow the continuous improvement of building stock energy efficiency characterization.
- Offer vocational training and educational content to inform the largest possible part of the building professionals and house owners about designing, building, and operating high-performance buildings.
- Communicate and inform the citizens about the benefits of clean domestic heating and energy efficiency in bringing jobs, economic prosperity, and better outdoor and indoor air quality in the Polish-built environment. There is a need to introduce smart energy meters and indoor environmental quality meters to quantify buildings' performance and allow occupants to visualize the benefit of investing in clean energy efficiency measures and RES.
- Support and increase the preparedness level of all stakeholders involved in the Architectural, Engineering, and Construction (AEC) Industry towards climate neutrality [112]. Non-governmental organizations such as the Polish Green Building Council or the Polish Passive Hause Standards can improve the design, construction, and use of buildings in Poland so that sustainable construction becomes standard. The preparation should include capacity building of local and central government authorities about ensuring the quality of energy and carbon-neutral buildings.

5.2. Strengths and limitations

As part of this study, more than 120 documents were reviewed, and 12 experts were interviewed through intensive focus discussions. Moreover, most of the authors of this study are Polish experts who

Table 6
Proposal for future building requirements in the residential sector.

Requirements for new construction: Single Family/ Multi-Family	2020	2030	2050
Primary Energy (heating, ventilation and DHW)	70/65 kWh/ m^2/a	45/50 kWh/m^2/ a	45/50 kWh/ m^2/a
Renewables as a percentage of total primary energy	20/15%	40/30%	100%
Carbon operational emissions	–	15-20 $kgCO_2$ equivalent/m^2	0-$kgCO_2$ equivalent/m^2

witnessed the evolution and transformation of the Polish building stock. Hence, the study provides a current snapshot of the status quo of energy efficiency in Poland after introducing the EPBD and after reaching the E.U.'s Horizon of 2020. The analysis allows presenting valuable insights on building energy requirements for Poland, which falls in the European continental climatic zone [113]. Also, the analysis presents future perspectives on the EU 2030 plan of achieving a 55% net carbon reduction under the Fit for 55 package and the European Green Deal and the 2050 EU climate neutrality target, based on exchanges with local and international experts. It takes into account the EPBD definitions, metrics, and calculation methodologies such as cost optimality including the 2021 EPBD recast that aims to suggest a carbon pricing approach in line with the EU Emissions Trading System (ETS).

To the best of our knowledge, this is the first comprehensive study using a literature review and focus group discussions on identifying the status quo of residential building energy efficiency in Poland. The results are validated through different triangulation methods to assure the consistency and soundness of the recommendations. More importantly, the study identifies the key threats and gaps in the Polish legislative landscape towards buildings compatible with the EPBD 2050 carbon neutrality vision.

Needless to say, the study bears many shortcomings. The literature review was limited to available documents that are accessible online. Also, the FGD were conducted with a small sample of stakeholders and did not include politicians, energy companies, or construction companies. Other studies or reports on energy efficiency financing were not screened thoroughly. Studies that address renovation and thermo-modernization were considered second priority compared to studies that addressed new construction concepts such as PH, nZEB, or NZEB and the associated technical and financial aspects. However, the study provides a genuine review that can benefit the Polish government, scientists, and professionals besides the European Commission.

5.3. Implications on practice and future research

Poland has a strong history of energy efficiency standards evolution that has been aligned to the EPBD standard during the last decade. The latest version of the Polish standards largely adopted most of the EPBD recast requirements. However, Poland shall update its energy efficiency policies for the residential building sector and increase all relevant stakeholders' preparedness. The EPBD recast of 2018 and 2021 promotes equal access to financing for energy-poor citizens and social housing while considering affordability. The new revised EPBD recast that will be published in 2021 requires all buildings constructed as of January 2030 to be positive energy/net-zero carbon over the life cycle [114]. However, without clustering and benchmarking the existing residential building stock and identifying the worst-performing segments in terms of indoor air quality and energy use intensity, it will be difficult to improve energy efficiency. Identifying worst-performing segments will help the national and local governments support energy-poor occupants located in air polluted neighborhoods and provide financial support in subsidies. It will only be possible to continue developing and enforcing the EPBD implementation and focusing on inspections on energy efficiency technology solutions and HVAC systems. This will allow continuing to apply requirements for a certain level of energy performance for rental and ownership properties according to the energy performance certificates. Moreover, a green building rating system for residential buildings needs to be developed or adopted to expand the country's progress toward sustainability.

Moreover, Poland has a high potential to tackle air pollution in its cities and decarbonizing heating in the residential sector through leapfrogging. Switching to heat pumps sourced from solar PV can skip the stage of natural gas transition, enabling Poland to catch up sooner with building carbon neutrality. Despite the cost challenges, the legislation and financial landscapes must pull the Polish building sector to leapfrog.

Future research should also close the gaps identified in this study. There should be more research on indoor thermal and air quality, alternative heating systems, and more comparative studies that embrace the cost optimality approach. The cost-optimality methodology should be investigated and used to assess Poland's energy efficiency and influence the regulation. Future research shall also examine the impact of the current and future EPC scheme of energy efficiency in Poland's residential buildings. Climate change effects and the electrification of high-performance houses are essential topics for future investigation.

6. Conclusion

The paper provides an overview of the state-of-the-art of energy efficiency in the Polish residential building stock. To prepare for that review, the authors took a series of steps to gather evidence to extend the Polish residential building stock's energy efficiency address, focusing on what worked and what could be improved. Eighty documents were reviewed and grouped under seven themes (see Fig. 2). A SWOT analysis was created based on FGD with 14 Polish experts. The Polish energy efficiency sector is under remarkable and fast transformation. Financial support, education, and legislation will play a major role in boosting this carbon-neutral sector transition. Unlike many EU countries, cleaner heating for energy-poor households and air-polluted neighborhoods should be the core of any Polish energy efficiency legislation. Financial incentives and financial institutions should focus on cleaner heating for energy-poor households and air-polluted areas for energy efficiency renovations in buildings. In parallel, the improvement and enforcement of the energy performance certificates will significantly improve buildings' energy performance. The current certification scheme is flawed and does not play a central role as expected in Poland. Consolidating the certification scheme and inspections will characterize the residential building stock and focus on the renovation on fuel poverty and air quality. In addition to purpose and objectives, the certificates should also disclose cost-effective ways and, where appropriate, available financial instruments to improve the building's energy performance to the buildings' owners or tenants. The EPC development should be coupled to the cost-optimal calculation method proposed by the EPBD to determine better cost-optimal energy conservation measures, RES, and incentives programs. Decarbonizing heating is absolutely critical to stand a chance of meeting net-zero emissions goals. Poland is taking serious steps towards energy efficiency but it requires further consolidation and acceleration to contribute to the wider EU's objective of a highly energy-efficient and decarbonized building stock by 2050.

Credit author statement

Shady Attia: Conceptualization, Supervision, Methodology, Draft preparation, Writing- Original, Validation, Visualization, Draft preparation, Reviewing and Editing. Piotr Kosiński: Conceptualization, Draft preparation, Validation, Reviewing and Editing. **Robert Wójcik: Reviewing and Editing. Arkadiusz Węglarz: Reviewing and Editing. Dariusz Koc: Reviewing and Editing. Oriane Laurent: Draft preparation, Software, Data curation, Validation, Visualization.**

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper..

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Appendix I

Table A
list of the Polish authors work that was reviewed and classified according to five thematic categories

	Economy	Energy sources	Policies & regulations	Education & Skills	Thermal Comfort	Building technologies	Outdoor Air Quality
Adamczyk and Dylewski [22]			✓				
Basińska [17,115]			✓				
Bekierski [45]			✓				
Berent-Kowalska [28]			✓				
Brągoszewska [62,92]							✓
Chmielewska [75]	✓		✓			✓	
Cholewa [38,74,76]		✓					
Chwieduk [42,80,116]		✓				✓	
Czaplicka-Kolarz [117]		✓				✓	
Dudzińska [118,119]			✓		✓		
Dworakowska [2]			✓				
Fedorczak-Cisak [59,60,63,67]			✓		✓		
Ferdyn-Grygierek [58,61,65]			✓		✓	✓	
Firląg [21,51]	✓		✓			✓	
Flaga-Maryanczyk [78]						✓	
Gołąbeska [23]	✓						
Grygierek [120]						✓	
Jarnut [84]						✓	
Kisilewicz [67,118,119]					✓	✓	
Kosiński [64]						✓	
Kostka [121]					✓		
Kozielska [62,89,92,93]					✓		✓
Krawczyk [29]	✓						
Księżopolski [8]	✓						
Kwiatkowski [52]			✓				
Małgorzata [33,56,59,67,75,115]			✓	✓	✓	✓	
Napierala [54]				✓			
Nemś [79]						✓	
Pawłowski [41]			✓			✓	
Piasecki [51,63]			✓			✓	
Ratajczak [86,115]			✓		✓		
Romańska-Zapala [122]						✓	
Skoczkowski [9,31]		✓					
Skorek-Osikowska [123]						✓	
Skotnicka-Siepsiak [124]						✓	
Sowa [48,87]			✓		✓		
Staniaszek [15,20]	✓						
Starościk [125]						✓	
Strawiński [126]				✓			
Suszanowicz [85]						✓	
Tomaszewska [127]						✓	
Węglarz [9,27,31,33,50,56,103]	✓		✓	✓	✓	✓	
Więcka [56]				✓			
Wójcik [35,64]			✓			✓	
Wojdyga [73]						✓	
Zaborowski [2,33]			✓				
Zimny [77,95]		✓	✓			✓	
Życzyńska [38]			✓				

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