Improving the thermal performance of existing buildings in light of the requirements of the EU directive 2010/31/EU in Poland

Abstract: Nowadays, the issue of energy saving is becoming increasingly important. Both households and large public facilities, such as schools, kindergartens, health centers, shopping, or leisure centers, implement energy saving systems. To start saving, one must first identify where the greatest energy losses occur. For this purpose, energy audits are carried out. The results of the audit make it possible to implement the necessary changes, including the replacement of old heating systems with modern energy-efficient equipment with the same, or even better, heating effect. This article presents research conducted in two public buildings, namely the Elementary School in Powroźnik in the administrative district of Muszyna and the Municipal Sports and Recreation Center in Dębica in Poland. The tests were carried out in accordance with the Directive 2010/31/EU (with later changes: directive 2012/27/EU and (EU)2018/844). The obtained results confirmed the need for comprehensive thermal upgrades in both buildings. The objective of the research was to develop the method aimed to reach the nearly zero-energy building in a public sector. Buildings in this category are usually of the great volume and heating space, but the functions of the buildings may be very diverse. It can be an administrative office, school, swimming pool, ice rink, hospital, etc. The article shows that although the functions of the buildings can be different some common methods of effective thermomodernization can be developed. In general, in large public buildings, complex solutions should be implemented. These include heat recovery using heat pumps in ventilation systems, renewable energy sources, such as photovoltaics, heat pumps, or combined heat and power for space heating, building management systems that adjust the heat supplied according to the weather conditions, and lighting systems.

Keywords: thermal performance of buildings, energy auditing, heat recovery, building management system, climate protection

1 Introduction

Global environmental awareness is increasing every year. More and more people recognize the need for the rational use of fuels and energy, taking care of the natural environment, saving air, water, and land resources. The growing environmental movement is forcing national governments to pass and implement laws to protect our planet from devastation. To prevent a climate catastrophe, measures are being undertaken by various countries to reduce the use of fossil fuels and switch to renewable energy sources (RES). These include, among others, the commitments made during the Paris Agreement [1–6]. For years, the European Union has been at the forefront of activities aimed at decarbonizing national economies and achieving climate neutrality, through the so-called European Green Deal [7]. Intensive work is also underway on revising the clean energy for all Europeans package [8], European Climate Law [9], and Carbon Border Adjustment Mechanism [10], as well as on strengthening the EU Emissions Trading System (ETS) system for the next decade (EU ETS Revision for phase 4 [2021–2030]) [11], and the Just Transition Mechanism [12].

In Europe, the leading country in renewable energy is Germany. Country, which already in May 2011 adopted the Energiewende package aimed at the transition to renewable energy [13–18]. Among others, in the construction sector, it is planned to reduce CO2 emissions from 209 million tons in 1990 to 70–72 million tons in 2030, a reduction by 66–67% [19]. The federal government will support the retrofitting of existing buildings and
implement high energy-efficiency standards. The demand for heating and cooling will be covered by RES.

The need to protect the climate is recognized by politicians and citizens of most countries in the world. It is a sign of the times that the United States has rejoined the Paris Agreement [20] on 21 January 2021.

2 Background

Poland has adopted the Act on RES [21], the Energy Efficiency Act [22], and the National Air Protection Plan [23], aimed at improving the air quality in Poland. This is particularly vital in areas with the highest concentrations of air pollutants and large population centers. One of the most recent documents regulating energy and environmental issues in Poland is the Energy Policy of Poland until 2040, adopted in February this year [24]. Numerous government documents, such as acts and regulations concerning buildings, heating, cooling, ventilation, and air conditioning, have also been adopted in Poland over the years [25–31]. Additionally, at the local level measures are being undertaken to encourage the implementation of the thermal upgrade of public buildings. The Provincial Fund for Environmental Protection and Water Management in Kraków cofinances the thermal upgrade of buildings, with assuming a minimum area of 600 m². Such subsidies are available for the following [32]:

- Hospitals or medical entities (up to 30%).
- Hospices (up to 60%).
- Cultural institutions (state and local government; up to 20%).
- Church legal entities (up to 30%).
- Research institutes and public universities (up to 20%).
- National parks (up to 20%).

Loans, which are granted for up to 100% of eligible net costs, have preferential interest rates. Similar activities are also carried out by other provincial funds, such as the Provincial Fund for Environmental Protection and Water Management in Warsaw [33], Lublin [34], Łódź [35], Wroclaw [36], Poznań [37], Gdańsk [38], Katowice [39], and many other provincial cities.

In addition to the fear of an ecological disaster that can result from overexploitation of the planet’s resources, there is a growing generation that recognizes the potential negative effects of such management. As pointed out by Fücks [40], there is a trend in wealthy societies to move away from accumulating material possessions to satisfying other needs, such as self-realization or learning about oneself and the surrounding world. Above a certain threshold of prosperity, it is no longer about “more” but “better.” Such an approach to life gives hope that the environment can be preserved to ensure that future generations can function at a level no worse than today.

In Poland, coal is still the main energy source for household heating. As much as 87% of coal burned in the EU for individual heating purposes is consumed in Poland [41]. However, this situation will change as the decarbonization of the power sector progresses. A similar trend develops by the space heating. According to an analysis carried out by the Forum Energii, around 1.5 million heat pumps could be installed in Poland by 2030, which would make it possible to replace almost half of the coal-burning furnaces and boilers used today. The authors of this report believe that Poland needs a vision for the transformation of the heating sector and a strategy that will achieve its goals of clean air, increased energy efficiency, and minimized climate impact of the energy sector.

Energy management in buildings is also an important issue. There are many systems for energy management in buildings, and the most effective are Building Management Systems (BMS), that is, advanced technical solutions aimed at efficient control of installations in a building, such as electrical, ventilation, heating, and cooling systems, and adjusting their operation to changing conditions [42,43].

Thermal efficiency improvement will be carried out at such a pace to meet the goal of zero-emission buildings by 2050 [44]. This is important as most Poles live and work in insufficiently insulated buildings. It is estimated that this problem affects 72% of detached houses (approximately 3.6 million), 50% of multifamily residential, and approximately 70% of nonresidential buildings [45]. Currently, the “Clean Air” program is being implemented in Poland [46]. It is a program targeted at owners and co-owners of detached houses. Under this program, it is possible to obtain a grant to replace old and inefficient solid fuel heat sources with modern heat sources meeting the highest standards and to carry out the necessary thermal upgrade of the building. The maximum grant amount is up to 30,000 PLN for the basic financing level and 37,000 PLN for the increased financing level. The total amount allocated for this purpose is 103 billion PLN. According to the survey conducted by Market and Social Research Institute [47], as many as 70% of Kraków’s residents would like electricity in public buildings to come from renewable sources. Every second respondent would expect the municipality to make announcements about air quality, and nearly 43% want the municipality to inform its residents about air protection regulations.
Replacement of old inefficient appliances with new energy-efficient ones and thermal upgrade of buildings are costly but bring long-term benefits. These issues have been addressed by many authors in Poland [48–51], but each case requires individual analysis and calculation. Similar problems also exist in other countries [52,53] and must be analyzed on a case-by-case basis.

The Act on the Energy Performance of Buildings [54] and further regulations [55] connected with the Act require that the energy used for heating space and domestic hot water in a new building owned by the community council after 2020 cannot exceed $E_{PH+W} = 45 \text{ kW h/m}^2$. Similarly, low values are set for lighting ($E_{PL} = 50 \text{ kW h/m}^2$) and cooling ($E_{PC} = 25 \text{ kW h/m}^2$). These limits pose the same problems to project makers because the limits are set for 1 m² independent of the height of the building. For example, if the internal height of the story is 2.5 m, then $E_{PH+W} = 45 \text{ kW h/m}^2$ means 18 kW h/m². In the case of the story height of 16 m (like in sports halls), the same factor is 2.81 kW h/m³ (Figure 1).

To reach such a low factor, it is often not enough to insulate the walls and roof, even by the standard of passive houses, and use low-emission windows. Most of the energy in insulated buildings goes to heating the air during the ventilation process, especially if the volume of the building is significant, for example, in sport halls.

In this case, the primary energy factor EP was exceeded in all aspects (space heating, domestic hot water, air conditioning, and lighting), although the window wall and ceilings insulations as well as light-emitting diodes (LED) lamps were designed according to passive house standards. In addition, the ventilation system was equipped with a heat exchanger of 68% efficiency.

Figure 2 shows that the key to solving the problem of the use of primary energy over the limit of space heating is to reduce ventilation losses. The solution aimed at and developed in the energy audit is to introduce a ventilation unit equipped not only with a passive heat exchanger but also with an air/air heat pump. This increases the recuperation efficiency over 95% during an average heating season. This solution not only recovers heat but also reduces the energy used for air conditioning. Two problems seemed to be solved by one unit. Unfortunately, heat pumps use electric energy, and the demand for electric energy by the ventilation system increases seasonally. Electric energy in Poland has its primary energy factor equal to three because our power plants are mostly supplied with coal. Electric energy produced this way is equal to one-third of the chemical energy of coal and two-thirds is waste heat. Hence, although the final energy use by heat pumps is very limited due to very good coefficient of performance (COP) of the heat pump, the primary energy use is still high.

To solve the next problem, it is necessary to reduce the consumption of electric energy using photovoltaics (PV) installations, for example. A PV system reduces the demand for the primary energy through utilizing RES directly from the sun.
3 Method

Directive 2010/31/EU [57] at the article 7 (existing buildings) states:

“Member States shall take the necessary measures to ensure that when buildings undergo major renovation, the energy performance of the building or the renovated part thereof is upgraded in order to meet minimum energy performance requirements set in accordance with Article 4 in so far as this is technically, functionally and economically feasible.” This means that an existing building does not have to meet the requirement of $E_{PH+W}=45$ kW h/m² like in the example above, but it is important to balance the cost and results so as not to do things which are unfeasible economically.

### 3.1 Case 1: elementary school at Powroźnik community Muszyna

The Elementary School at the Powroźnik Community in Muszyna is a building from the 1970s. The heating space is 3511.41 m² (Figure 3).

About 10 years ago, the building was insulated with 5 cm thick polystyrene, so thermal transmittance of the walls was on the level $U=0.3$ W/Km². The thermal transmittance for the roof was $U=0.6$ W/Km² and $U=2.6$ for the windows. The boilers were replaced and thermosolar system was already developed. The ventilation system is natural and the heating system is based on gas boilers. The energy used by the school building is shown in Table 1 and the calculation of $E_p$ factor is shown in Table 2.

Based on the results of the energy audit, the following solutions were proposed:

1. Isolation of the roof with rock wool of $\lambda = 0.035$ (W/[m K]) and 14 cm thickness
2. Isolation of the external walls using 8 cm polystyrene of $\lambda = 0.036$ (W/[m K])
3. Isolation of the floor on the ground floor using 10 cm polystyrene of $\lambda = 0.036$ (W/[m K])
4. Replacing the windows with new ones of $U < 0.9$ (W/[m² K])
5. Implementation of a mechanical ventilation system using ventilation units equipped with rotors as the heat exchangers and integrated heat pump as the second stage of recovering energy.

Figure 2: Space heating-energy losses (source: based on an earlier study [56]).
(6) Cascade of three new condensing gas boilers and two absorption heat pumps powered with natural gas. Total power of the set is 179.8 kW. Heat pumps alone about 70 kW.

(7) Energy control system based on the weather forecast. In terms of the electric energy:

(1) New light sources in LED technology inside and outside the building.

(2) PV system of 39.73 kWp.

In addition, BMS monitoring the energy for space heating, domestic hot water, lighting, and the rest of electric energy was applied. This means 2 m of the heat and two of electric energy were integrated with controlling program. The results are as follows:

The single increase by auxiliary energy comes from the heat pumps working in the ventilation system, which is only partially compensated by the PV system.

Generally, the reduction of the energy demand of the building reaches 75%.

The values presented in the tables are the results of calculations made within the energy audit based on the monthly method. The real gas consumption for space heating in the year 2018 was 530,896 kW h, which is about 11% less than the calculated value. The calculation was made using temperatures in a standard heating season as defined by the Polish Ministry of Infrastructure. The year 2018 was warmer than the standard values. For example, according to the Institute of Meteorology and Water Management National Research Institute \[58\], the temperature of January 2018 was of about 3°C higher than the average value in years 1971–2000.

Table 1: Energy demand of the building

| Description | Heating + ventilation | Domestic hot water | Cooling | Lighting | Auxiliary energy | Total |
|-------------|-----------------------|--------------------|---------|----------|------------------|-------|
| School      | 590,219               | 71,500             | 0       | 73,323   | 5,832            | 740,874|

Source: own study.
The external temperature anomaly explains the difference between calculated values and those measured by the gas counter.

### 3.2 Case 2: The heat recovery from an artificial ice rink

A sports complex in Dębica consists of an ice rink and swimming pools. Everything is arranged in one great hall divided into two parts (Figure 4).

The existing equipment was separated before the energy audit has started.

The ice rink was cooled with an old cooling machine, which returned the heat from cooling into the atmosphere. However, the swimming pool was supplied with energy from the district heating.

The idea to use heat recovered from the ice rink for heating the swimming pool was considered in the energy audit provided by Tomasz Sumera.

A high power heat pump with a cooling capacity of 403 kW and heating power of 560 kW was considered in the project. A heat pump using CO₂ refrigerant (R744) is also better for the environment and human health than the old system, which uses ammonia.

### 4 Results and discussion

Both examples show the increasing role of proper use and preserving the internal heat gains of the building. Increasingly sophisticated methods and equipment should be used to reach the goal, which is the nearly zero or very low amounts of energy required per building. The first case shows that preserving the energy in the building, sometimes, can be the most effective way to reduce than using RES. The ventilation system takes a very important role in reducing the energy demand of the building. High-effective ventilation unit consists of the rotation heat exchanger of maximum efficiency about 80% and also a heat pump air/air, which works with a very high COP level over five and heats the incoming air after the rotation heat exchanger using the energy gained from the exhaust air. Of course, it increases the electric energy demand of the building because the new ventilation units require electric supply and the previous ventilation system was the natural one. The photovoltaic system reduces the demand of the electric energy. To recover 100% of the thermal energy given back by the ventilation units, the internal heat pumps at the ventilation system use electric energy on the level of only about 20% of the thermal energy recovered. This is possible due to COP > 5 of the heat pumps working in ventilation system. In such case, covering the additional demand of the electric energy by a photovoltaic system is a very efficient solution. It reduces the external energy electric demand to a level almost zero. Parallelly, the heat recovery at the ventilation system reduces the demand of the thermal energy demand to the level, which would not be possible to reach due to the isolation of the building only (Table 3).

The second case – the energy recovery from the ice rink shows a great potential for saving the energy by the heat recovery form one part of the building to another or even between two separated buildings located nearby.

### Table 2: Factors: $E_{\text{PH-W}}$, $E_{\text{PL}}$, and $E_{\text{PH-W-L}}$ (kW h/m²)

| Description | Total energy for heating and domestic hot water | Heating space (m²) | $E_{\text{PH-W}}$ indicator | $E_{\text{PL}}$ indicator | $E_{\text{PH-W-L}}$ indicator |
|-------------|-----------------------------------------------|-------------------|---------------------------|--------------------------|-----------------------------|
| School      | Before modernization                          | 667,551           | 3511.41                   | 190.11                   | 20.88                       | 210.99                      |

Source: own study.
Table 3: Energy saving after modernization

| Description | Heating + ventilation | Domestic hot water | Cooling | Lighting | Auxiliary energy | Total |
|-------------|-----------------------|--------------------|---------|----------|-----------------|-------|
| School      |                       |                    |         |          |                 |       |
| Before modernization (kWh/year) | 590,219 | 71,500 | 0     | 73,323 | 5,832 | 740,874 |
| After modernization (kWh/year)   | 82,684   | 54,017  | 0     | 39,381 | 8,303 | 184,384 |

Energy reduction (kWh/year) 507,536 17,483 33,942 −2,471 556,490

% 85.99 24.45 46.29 −42.37 75.11

Source: own study.

Table 4: Energy saving due to the heat recovery at the ice rink

| Month | Heat pump electricity consumption (MWh) | Heat recovery by heat pump | The heat consumption of the MOSiR\textsuperscript{1} facility in Dębica based on invoices | Saving heat energy from MPEC\textsuperscript{2} by using a heat pump (GJ) |
|-------|----------------------------------------|---------------------------|-------------------------------------------------|-------------------------------------------------|
|       |                                        | MWh | GJ                 | Space heating of cloakroom at the ice rink + swimming pool (GJ) | Swimming pool (GJ) | Domestic hot water. Ice rink + swimming pool (GJ) | Total MOSiR facilities (GJ) |
| 1     | 83.160                                 | 248.648 | 895.132 | 909.000 | 516.000 | 208.000 | 1633.000 | 895.132 |
| 2     | 47.600                                 | 142.324 | 512.367 | 805.000 | 468.000 | 201.000 | 1474.000 | 512.367 |
| 3     | 62.472                                 | 186.790 | 672.444 | 789.000 | 420.000 | 168.000 | 1377.000 | 672.444 |
| 8     | 96.240                                 | 287.757 | 1035.925 | 13.700 | 91.500 | 16.900 | 122.100 | 122.100 |
| 9     | 65.008                                 | 194.373 | 699.743 | 164.300 | 156.200 | 109.400 | 429.900 | 429.900 |
| 10    | 64.791                                 | 193.725 | 697.411 | 569.400 | 337.300 | 138.000 | 1044.700 | 697.411 |
| 11    | 60.000                                 | 179.401 | 645.843 | 655.300 | 390.000 | 156.700 | 1202.000 | 645.843 |
| 12    | 62.622                                 | 187.241 | 674.066 | 743.800 | 424.600 | 168.500 | 1336.900 | 674.066 |
| Sum   | 541.893                                | 1620.259 | 5832.931 | 4649.500 | 2803.600 | 1166.500 | 8619.600 | 4649.263 |

\textsuperscript{1}MOSiR, Municipal Sports and Recreation Center and \textsuperscript{2}MPEC, Municipal Heat Supply Company.

Source: own study.
The calculations made at the energy audit showed that the proper use of the internal heat gains, via transfer from the zone where they are useless to the zone where the energy is needed can be more effective than simple isolation of the envelope of the building or using RES. The examples are shown in the table below. The calculations are made based on the Polish price levels.

The heat recovery shown in Table 4 is 4649.263/8,619 = 54%.

During the cooling season, the heat pump will use 106,637 MW h = 383.9 GJ of electric energy, so the building’s final energy consumption reduction will be (4649.263–383.9)/8,619 = 49.1%.

The thermal energy consumption of the sports facility given in Table 4 (ice rink and swimming pool) is counted by proper energy meters. The electric energy consumption and the heat produced by the heat pump were calculated in the energy audit. Selection of the heat pump was based on the cooling capacity of existing equipment as evidenced checked by about 20 years of operation, and only the energy efficiency of the old machines was low.

In both cases (1 and 2), the calculations of the improvements have been made in MS Excel using formulas implemented by the author. The energy demand at each variant separately was calculated by the dedicated polish programs for calculation of an energy performance of buildings. Developing our own formulas has been necessary because the norm [59] gives no solution for calculation of the internal energy gains that can be transferred to another building or a separate section of the building in other way than through the walls, ceilings, or ventilation system. Our formulas are based on the basic law of conservation of energy and the technical parameters of the heat pumps used in calculation (such as COP, heating capacity, and cooling capacity) The calculations have been confronted with the energy measured by the proper meters and reached the proper accuracy.

The payback time was calculated at the tables according to the formula (Table 5):

$$\text{Simple Pay Back Time (SPBT)} = \frac{N_u}{\Delta O_{nu}},$$

where $N_u$ – cost of implementing the modernization. Annual cost savings $\Delta O_{nu} = (Q_{ou} - Q_{iu})O_z + 12(q_{ou} - q_{iu})O_m$

The best variant of thermosulation of the walls of the building using Styrofoam shows 73.2 years payback time (Table 6).

The example above shows the payback time of a photovoltaic installation.

The heat recovery by the heat pump installation was calculated in Table 4. The heat recuperation level is 4649.263 GJ (54% of the heat demand of the swimming pool; Table 7).

The examples show that the heat recovery system calculated in the energy audit gives two advantages:

1. best payback time from the modernizations considered above and
2. highest energy level gained by the system.

The previous technical norms and current one: EN ISO 52016-1:2017 [60].

“Energy performance of buildings – energy needs for heating and cooling, internal temperatures, and sensible and latent heat loads – Part 1: Calculation procedures” describes how to calculate the internal heat gains and

### Table 5: Payback time of the isolation of external walls of the building of the ice rink

| No. | Overview | Unit | Before thermos-modernization | Variants |
|-----|----------|------|------------------------------|----------|
| 1   | Thickness of an additional layer of thermal insulation $g$ | M | 0.02 | 0.05 |
| 2   | Increase of the thermal resistance $\Delta R$ | m$^2$ K/W | 0.6 | 1.6 | 2.5 |
| 3   | Thermal resistance $R$ | m$^2$ K/W | 3.46 | 4.1 | 5.0 | 6.0 | 7.2 |
| 4   | $Q_{ou}$, $Q_{iu}$ = 8,64 × 10$^{-5}$ Sd A $U_c$ | GJ/a | 7.7 | 6.3 | 5.3 | 4.4 |
| 5   | $q_{ou}$, $q_{iu}$ = 10$^{-5}$ A $(t_{ou} - t_{iu}) U_c$ | MW | 0.001 | 0.001 | 0.001 |
| 6   | Annual cost savings $\Delta O_{nu} = (Q_{ou} - Q_{iu})O_z + 12(q_{ou} - q_{iu})O_m$ | PLN/a | 72.80 | 145.60 | 234.23 | 244.40 |
| 7   | Unit price of improvements | PLN/m$^2$ | 143.00 | 153.00 | 158.30 | 175.50 |
| 8   | Cost of implementing the modernization $N_u$ | PLN | 15486.90 | 16569.90 | 17143.89 | 19006.65 |
| 9   | $SPBT = N_u/\Delta O_{nu}$ | Years | 212.7 | 113.8 | 73.2 | 77.8 |
| 10  | $U_c$ | W/m$^2$ K | 0.29 | 0.24 | 0.20 | 0.17 | 0.14 |

Source: own study.
energy transmitted from other zones through the walls and other building elements. There is no ready procedure how to include the heat gain transferred from one part of the building to another in other ways than natural transition through the building elements in the calculations. In our opinion, it should be taken into consideration by reviewing the norm.

5 Conclusion

Based on the obtained results, it can be stated that an energy audit in public buildings may be complicated, especially if one wants to meet the requirements of the Directive 2010/31/EU (with later changes: directive 2012/27/EU [60] and (EU) 2018/844 [61]).

To solve this problem, a complex solution is necessary, including, but not limited to heat recovery using heat pumps in ventilation systems, RES such as photovoltaics, heat pump or heating and cooling systems for space heating, building management system that automatically controls space heating based on the weather forecast, and lighting depending on the natural sunlight levels in the building. Heat recovery from other sources can be used where possible; for example, waste heat from industrial production can be used for space heating in factory buildings, and heat recovered from artificial ice rinks can be used to heat swimming pools, etc.

Reaching the goal set by the directive 2010/31/EU (with later changes: directive 2012/27/EU and (EU) 2018/844), therefore, requires that the energy auditor thinks in a more interdisciplinary manner. The ice rink example shows that transmitting the internal heat gains from one part of the building to another or even between two buildings located nearby can improve the energy efficiency and maximize the internal heat gain factor in both buildings. By reviewing the norms regarding energy performance of buildings, this problem and potential updates to the norm should be considered.

Summing up, it should be stated that measures to reduce the consumption of chemical energy contained in fossil fuels are undertaken in many countries, especially in the EU. The effects of these activities are visible in the data showing the final energy consumption. The decline in energy consumption is particularly visible in highly developed countries such as the United Kingdom, Germany, France, and Italy [62].

Due to the work carried out in two public buildings in Poland and presented in this article, the consumption of chemical energy contained in fossil fuels is reduced, which in turn reduces CO$_2$ emissions and helps to protect the Earth’s climate.

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References

[1] Paris Agreement 2015. https://ec.europa.eu/clima/policies/international/negotiations/paris_en. Accessed on 20 March 2021.

[2] The Katowice climate package: Making The Paris Agreement Work For All. https://unfccc.int/process-and-meetings/the-paris-agreement/katowice-climate-package. Accessed on 20 Mar 2021.

[3] The Katowice Rulebook – main principles of the document, https://cop24.gov.pl/news/news-details/news/the-katowice-rulebook-main-principles-of-the-document/.

[4] COP24 zakonczony sukcesem (Successful conclusion of COP24 in Katowice) https://www.gov.pl/web/klimat/cop24-zakonczony-sukcesem (In Polish), Accessed on 20 Mar 2021.

[5] 2020 climate & energy package. https://ec.europa.eu/clima/policies/strategies/2020_en Accessed on 18 April 2021.

[6] Clean energy for all Europeans file: //C:/Users/olkus/AppData/Local/Temp/MicrosoftEdgeDownloads/82ed772bc226-4a07-bb79-ad55e3882571/M0319092ENN.en.pdf. Accessed on 18 April 2021.

[7] A European Green Deal. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. Accessed on 28 April 2021.

[8] Clean energy for all Europeans. https://op.europa.eu/en/publication-detail/-/publication/b4e46873-7528-11e9-9f05-01aa75ed71a1/language-en. Accessed on 28 April 2021.

[9] European Climate Law. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0080. Accessed on 27 April 2021.

[10] Carbon Border Adjustment Mechanism. https://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupMeetingDoc&docid=45168. Accessed on 28 April 2021.

[11] Revision for phase 4 (2021–2030). https://ec.europa.eu/clima/policies/ets/revision_en. Accessed on 12 April 2021.

[12] The Just Transition Mechanism: making sure no one is left behind. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/actions-being-taken-eu-just-transition-mechanism. Accessed on 27 April 2021.

[13] Jahresbericht der Bundesregierung 2011/2012. ENERGIE DER ZUKUNFT. DIE ENERGIEWENDE. https://www.bundesregierung.de/statistich/jb11-12/Webs/Breg/DE/Themen/Jahresbericht_2011_2012/03_Energie/i/Energiewende/_node.html (In German). Accessed on 19 April 2021.

[14] Energiewende – die Gesetze. Archiv von bundesregierung.de. Die Bundesregierung. https://archiv.bundesregierung.de/archiv-de/energiewende-die-gesetze-419168#:~:text=Gesetz%20zur%20Neuregelung%20energienachrichten%20Vorschriften%20%28EnWG%2C%20Energie%29%20Kerns%20C3%BCck%20Kernenergie,wirtschaftssouver%20Energievertrieb%20Verbraucher. Freitag, 5. August 2011 (In German). Accessed on 19 April 2021.

[15] Raport Niemiecka transformacja energetyczna. Trudne początki. (German energy transition report. A difficult start). Red. Anna Kwiatkowska-Drożdż. Centre for Eastern Studies im. Marka Karpia. Warszawa; 2012 (In Polish).

[16] Szyszalski W. Niemiecka Transformacja Energetyczna. Fakty. (Facts about the energy transition in Germany). Heinrich Böll Stiftung. Warszawa; 2015 (In Polish).

[17] From the abstract to the ordinary. Federal ministry of the environment, nature conservation and nuclear safety. https://www.bmu.de/en/report/from-the-abstract-to-the-ordinary/Published 17 October 2017.

[18] Kuittinen H, Velte D. Mission-oriented R&I policies: In-depth case studies. Case Study Report Energiewende. European Commission; January 2018.

[19] Amelang S, Wehrmann B, Wettengel J. Germany’s Climate Action Plan 2050. Clean Energy Wire. 21 Mar 2019. https://www.cleanenergywire.org/factsheets/deutschlands-climate-action-plan-2050. Accessed on 19 April 2021.

[20] UN Welcomes US Announcement to Rejoin Paris Agreement. https://unfccc.int/news/un-welcomes-us-announcement-to-rejoin-paris-agreement. Accessed on 15 April 2021.

[21] Ustawa o odnawialnych źródłach energii (Renewable Energy Sources Act), https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20150000478/U/D20150478Lj.pdf (In Polish).

[22] Ustawa o efektywności energetycznej (Energy Efficiency Act). http://isap.sejm.gov.pl/isap.nsf/DocDetails.aspx?id=wdu20160000831&type=2 (In Polish).

[23] Krajowy Program Ochrony Powietrza do roku 2020 (z perspektywą do 2030) (National Air Quality Programme until 2020 (with an outlook to 2030)). Ministerstwo Środowiska, Departament Ochrony Powietrza; Warszawa 2015 (In Polish).

[24] Polityka energetyczna Polski do 2040 r. (PEP2040). Ministerstwo Klimatu i Środowiska. Załącznik do uchwały nr 22/2021 Rady Ministrów z dnia 2 lutego 2021 r. Warszawa 2021. (In Polish) (Energy Policy of Poland until 2040 (EPP2040). Ministry of Climate and Environment. Annex to Resolution No. 22/2021 of the Council of Ministers of February 2, 2021, Warsaw 2021). https://www.gov.pl/web/klimat/polityka-energetyczna-polski. Accessed on 1 March 2021.

[25] Obwieszczenie Ministra Infrastruktury i Rozwoju z dnia 17 lipca 2015 r. w sprawie ogłoszenia jednolitego tekstu
rozporządzenia Ministra Infrastruktury w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie. Załącznik 2. Wymagania izolacyjności cieplnej i inne wymagania związane z oszczędnością energii (Anouncement of the Minister of Infrastructure and Development of 17 July 2015 regarding the publication of a uniform text of the Regulation of the Minister of Infrastructure on the technical conditions which should be met by buildings and their location. Annex 2. Thermal insulation requirements and other requirements related to energy saving. Journal of Laws 2015, item 1422).

[26] Rozporządzenie Ministra Infrastruktury i Budownictwa z dnia 20 grudnia 2016 r. zmieniające rozporządzenie w sprawie metodologii wyznaczania charakterystyki energetycznej budynku lub części budynku oraz świadectw charakterystyki energetycznej. Dz.U. 2017, poz. 22 (Regulation of the Minister of Infrastructure and Construction of 20 December 2016 amending the regulation on the methodology of determining the energy performance of a building or part of a building and energy performance certificates. Journal of Laws 2017; item 22).

[27] Rozporządzenie Ministra Infrastruktury z dnia 12 kwietnia 2002 r. w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie. Dz.U. 2002 Nr 75, poz. 690 (Regulation of the Minister of Infrastructure of 12 April 2002 on technical conditions to be met by buildings and their location. Journal of Laws 2002; No 75, item 690).

[28] Rozporządzenie Ministra Infrastruktury z dnia 21 stycznia 2008 r. w sprawie przeprowadzania szkolenia oraz egzaminu dla osób ubiegających się o uprawnienie do sporządzania świadectwa charakterystyki energetycznej budynku, lokalu mieszkalnego oraz części budynku stanowiącej samodzielne całość techniczno-uzytkową. Dz.U. 2008 Nr 17, poz. 104 (Regulation of the Minister of Infrastructure of 21 January 2008 on conducting training and exam for persons applying for the right to draw up energy performance certificates for a building, flat and building part constituting an independent technical and utilitarian whole. Journal of Laws 2008; No 17, item 104).

[29] Rozporządzenie Ministra Infrastruktury z dnia 6 listopada 2008 r. zmieniające rozporządzenie w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie. Dz.U. 2008 Nr 201, poz. 1238 (Regulation of the Minister of Infrastructure of 6 November 2008 amending the regulation on technical conditions that should be met by buildings and their location. Journal of Laws 2008 No. 201, item 1238).

[30] Rozporządzenie Ministra Infrastruktury z dnia 6 listopada 2008 r. zmieniające rozporządzenie w sprawie szczegółowego zakresu i formy projektu budowlanego. Dz.U. 2008 Nr 201, poz. 1239 (Regulation of the Minister of Infrastructure of 6 November 2008 amending the ordinance on the detailed scope and form of a construction project. Journal of Laws 2008 No. 201, item 1239).

[31] Ustawa z dnia 27 sierpnia 2009 r. o zmianie ustawy – Prawo budowlane oraz ustawy o gospodarce nieruchomościami. Dz.U. 2009 Nr 161, poz. 1279 (Act of 27 August 2009 amending the act – Construction law and the act on real estate management. Journal of Laws 2009; No 161, item 1279).

[32] Termomodernizacja. Wojewódzki Fundusz Ochrony Środowiska i Gospodarki Wodnej w Krakowie (Thermal upgrade. Provincial Fund for Environmental Protection and Water Management in Kraków) https://www.wfos.krakow.pl/oferty/termomodernizacja-5/ (In Polish). Accessed on 24 April 2021.

[33] Termomodernizacja – jak otrzymać wsparcie finansowe. Wojewódzki Fundusz Ochrony Środowiska i Gospodarki Wodnej w Warszawie (Thermal upgrade – how to receive a subsidy. Provincial Fund for Environmental Protection and Water Management in Warsaw), https://wfosigw.pl/termomodernizacja-jak-otrzymac-wsparcie-finansowe/# (In Polish). Accessed on 24 April 2021.

[34] Czyste powietrze. Wojewódzki Fundusz Ochrony Środowiska i Gospodarki Wodnej w Lublinie (Clean air. Provincial Fund for Environmental Protection and Water Management in Lublin), http://www.wfos.lublin.pl/czyste-powietrze.html, dostęp 24.04.2021 (In Polish). Accessed on 24 April 2021.

[35] Program Czyste Powietrze – rozliczenie dotacji, wniosk o płatność. Wojewódzki Fundusz Ochrony Środowiska i Gospodarki Wodnej w Łódź (Clean Air Programme - subsidy clearance, payment application. Provincial Fund for Environmental Protection and Water Management in Łódź). https://www.wfosigw.lodz.pl/aktualnosci/612-program-czyste-powietrze-rozliczenie-dotacji-wniosk-o-platnosc-2, (In Polish). Accessed on 24 April 2021.

[36] Czyste powietrze. Wojewódzki Fundusz Ochrony Środowiska i Gospodarki Wodnej we Wrocławiu (Clean air. Provincial Fund for Environmental Protection and Water Management in Wrocław). https://wfosigw.wroclaw.pl/czyste-powietrze/o-programie, dostęp (In Polish). Accessed on 24 April 2021.

[37] Program priorytetowy czyste powietrze. Wojewódzki Fundusz Ochrony Środowiska i Gospodarki Wodnej w Poznaniu (Clean air. Provincial Fund for Environmental Protection and Water Management in Poznań). https://www.wfosigw.poznan.pl/program-priorytetowy-czyste-powietrze/, (In Polish). Accessed on 24 April 2021.

[38] Czyste powietrze. Wojewódzki Fundusz Ochrony Środowiska i Gospodarki Wodnej w Gdańsku (Clean air. Provincial Fund for Environmental Protection and Water Management in Gdańsk). https://wfos.gdansk.pl/czyste_powietrze_icon, dostęp 24.04.2021 (In Polish). Accessed on 24 April 2021.

[39] Czyste powietrze. Oferta dla osób fizycznych. Wojewódzki Fundusz Ochrony Środowiska i Gospodarki Wodnej w Katowicach (Clean air. Offer for natural persons. Provincial fund for environmental protection and water management in Katowice). https://www.wfosigw.katowice.pl/oferta-dla-osob-fizycznych/program-czyste-powietrze.html (In Polish). Accessed on 24 April 2021.

[40] Fücks R. Zielona rewolucja (Title of the original in German: Intelligent Wachsen) Instytut Wydawniczy Książka i Prasa. Warszawa 2016 (In Polish).

[41] Rosenow J. Regulatory Assistance Project; Andrzej Rubczyński, Forum Energii; Piotr Kleinschmidt, Forum Energii. Elektryfikacja ciepłownictwa w Polsce. Droga do czystego ciepła. Forum Energii. https://forum-energii.eu/pl/analizy/elektryfikacja-ciepłownictwa. Published on 26 January 2021 r. (In Polish). Accessed on 24 April 2021.

[42] Węglarz A. Systemy grzewcze równie energetycznie efektywne. Vademecum. Budownictwo energetycznie efektywne, Heating systems including energy efficient ones. Vademecum. Energy efficient construction. Edycja; 2014 (In Polish).
[43] Węglarz A. Głęboka termomodernizacja budynków w Polsce. Zarządzanie energią w budynkach energooszczędnych – obiekty inteligentne. Thermal upgrade of buildings in Poland. Energy management in energy-efficient buildings – intelligent buildings. Rynek Instalacyjny 9/2015 (In Polish).

[44] Oko 4 mln domów jednorodzinnych wymaga termomoder-

[45] nizacji. Skąd wziąć na to środki? (About 4 million detached houses need thermal upgrade. Where to find the money?). Energetyka24. https://www.energetyka24.com/oko-4-mln-domow-jednorodzinnych-wymaga-termomodernizacji-skad-wziac-na-to-srodki Accessed on 3 March 2021 (In Polish).

[46] Firlaś S. Rynek termomodernizacji w Polsce. The renovation market in Poland. Rynek Instalacyjny 7-8/2016 (In Polish).

[47] Program czyste powietrze. (Clean air programme). https://czystepowietrze.gov.pl/czyste-powietrze/ (In Polish). Accessed on 24 April 2021.

[48] Pawlak U, Pawlak M. The thermomodernization of a single family house located in the Świętokrzyskie mountains – a case study. Sci Rev Eng Environ Sci. 2019;28(3):394–404. http://iks.pn.sggw.pl. doi: 10.22630/PNIKS.2019.28.3.37.

[49] Zender-Swiercz E, Piotrowski JZ. Thermomodernization a building and its impact on the indoor microclimate. Struct Environ. 2013;5(3):37–40. http://bc.tu.kielce.pl/231/1/Zender-Swiercz_Thermomodernization_SaE_3_2013.pdf, Accessed on 2 April 2021.

[50] Firlaś S. Cost-optimal plus energy building in a cold climate. Energies. 2019;12:3841. doi: 10.3390/en12203841, Accessed on 14 March 2021.

[51] Basiańska M, Kaczorzek D, Koczyn H. Building thermo-modernisation solution based on the multi-objective optimisation method. Energies. 2020;13(6):1433. doi: 10.3390/en13061433. Accessed on 14 March 2021.

[52] Zhao J, Du Y. A study on energy-saving technologies optimization towards nearly zero energy educational buildings in four major climatic regions of China. Energies. 2019;12:4734. doi: 10.3390/en12244734. file:///C:/Users/olkus/AppData/Local/Temp/MicrosoftEdgeDownloads/1009fd62-3a0b-47d2-a7d0-738f398ff93d/energies-12-04734-v2.pdf.

[53] Cho K, Cho D, Kim T. Effect of bypass control and room control modes on fan energy savings in a heat recovery ventilation system. Energies. 2020;13:1815. doi: 10.3390/en13071815.

[54] Ustawa z dnia 29 sierpnia 2014 r. o charakterystyce energetycznej budynków. (The Act of 29 August 2014. The Energy Performance of Buildings Law). Dz.U. Poz. 1200 (In Polish).

[55] Rozporządzenie Ministra Transportu, Budownictwa i Gospodarki Morskiej z dnia 5 lipca 2013 r. zmieniające rozporządzenie w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usuwanie. (Regulation of the Minister of Transport, Construction and Maritime Economy of 5 July 2013 amending the regulation on technical conditions to be met by buildings and their location) (In Polish).

[56] Sumera T. Audyt energetyczny przebudowy budynku do poziomu niskoenergetycznego, zgodnie z dyrektywą Parlamentu Europejskiego i Rady 2010/31/UE z dnia 19 maja 2010 r. w sprawie charakterystyki energetycznej budynków na przykładzie Hali Sportowej Jaskółka w Tarnowie (Energy audit for conversion of a building to a low energy level, in accordance with Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings on the example of Hala Sportowa Jaskółka in Tarnów), Przegląd Techniczny 6/2017 (In Polish).

[57] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF

[58] IMGW Warszawa: https://klimat.imgw.pl/pl/climate/monthly/2018/1/Winter. Accessed on 9th June 2021.

[59] ISO 52016–1:2017 Energy performance of buildings – Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads – Part 1: Calculation procedures.

[60] Directive 2012/27/EU of The European Parliament And Of The Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/UE and repealing Directives 2004/8/EC and 2006/32/EC.

[61] Directive (EU) 2018/844 of The European Parliament And Of The Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.

[62] Olkuski T, Suwała W, Wyrwa A, Żyśk J, Tora B. Primary energy consumption in selected EU Countries compared to global trends. Open Chem. 2021;19:503–10. doi: 10.1515/chem-2021-0046.