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DOCTORAL THESIS

URBAN-SCALE ENERGY MODELLING OF SOME RESIDENTIAL ENERGY FLEXIBLE BUILDINGS CLUSTERS IN POLAND

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SUMMARY

The thesis entitled '*Urban-scale energy modelling of some residential energy flexible buildings clusters in Poland*' is focused on **U**rban **E**nergy **M**odelling (UEM) field, by means of a home-developed research computer tool named '*Computational **T**ool for **E**nergy Efficiency **A**nalysis of an Energy **C**luster*' (TEAC). The *TEAC* software is capable to perform environmental-, economic- and energy-related analyses of residential areas of Poland. Software flexibility and advisability for numerous applications were presented and tested based on some exemplary **B**uilding **E**nergy **C**luster**s** (BECs) consisting of hundreds of single-family houses. Each of the presented examples is focused on a different issue, to show the possibilities and full potential of the *TEAC* software. Finally, two case studies are examined for residential neighbourhoods located in Lodz.

The dissertation consists of seven main chapters, lists of tables and figures, as well as eight appendices. The first chapter is a kind of introduction, within which the aims, as well as the following hypotheses of the dissertation, are formulated. Firstly, it is possible to use advanced energy computer simulations for the prediction and analyses of energy demand profiles both for a single building, as well as whole residential areas. Secondly, the **E**nergy **C**luster (EC) concept is appropriate for improvement in the energy economy of urban areas. Finally, it is possible to predict the energy demand of the analysed area, based on basic buildings' parameters, their mutual influences and interactions, and appropriate climatic data.

Chapter **2** provides the theoretical background, concerning most aspects related to the **U**rban **B**uilding **E**nergy **M**odelling (UBEM) methodology. In this chapter, a comprehensive state-of-the-art overview is presented for the UBEM field (see more in section **2.1**). Additionally, the actual overview of the Polish power system and the household sector is discussed, accordingly in sections **2.2** and **2.3**; the both aspects were used as a basis in the performed studies. Moreover, the general overview on how to improve buildings' energy efficiency (section **2.4**), as well as their sustainability (section **2.5**) is discussed. The EC concept is introduced, as the approach applied in the performed studies, focusing on various analyses of residential neighbourhoods (see more in section **2.6**). The **2.7** section shows the outline of some computational codes application for various types of analyses concerning both individual buildings and whole urban zones, especially by means of the *Energy Plus* software. Finally, the **A**rtificial **I**ntelligence (AI) applications for various building energy analyses is reviewed in section **2.8**; the AI is applied in the performed analyses.

In chapter **3** the list of performed studies, as well as applied assumptions are briefly described. It starts with the overview of applied procedure, as shown in section **3.1**. The procedure includes some preliminary

steps (which were performed just once, before any calculation), within which the **N**eural **N**etwork (NN) training process was essential; that process is presented in section **3.6**. The gathered data and information were used to develop the *TEAC* software, which is described in detail in section **3.7**. When implemented, the *TEAC* software can be used for some UBEM, as it is shown for some preliminary examples in section **3.8**. The overview of applied assumptions is shown in the remaining parts of this chapter. Those assumptions are listed in section **3.2**, while used weather data is presented in section **3.3**. The Polish household sector is examined using computational models of **R**epresentative **S**ingle-**F**amily **H**ouses (RSFH); it is discussed in section **3.4**, while the proposed building modernization variants are presented in section **3.5**.

In chapter **4** some comprehensive examples of residential ECs are studied. Each example dealing with hundreds of buildings, is focused on different issues, in order to show various capabilities of the *TEAC* software. Also, each case is summarized with some concluding remarks concerning the performed analyses. The first case (section **4.1**) deals with 25 hundred buildings randomly selected from the RSFH (square area, 50 by 50 parcels, all occupied). Examinations of this cluster are focused on energy-related analyses, presented especially by means of local heating and electricity **L**oad **D**uration **C**urves (LDCs). Those type of analyses allows validating the proposed building modernizations in order to select actions, which increase energy stability and safety of the local grid. Out of the performed study, it is possible to outline peak energy demands, as well as to shift time-distributed loads in order to flatten LDC for the analysed area. The second case (section **4.2**) concerns 25 hundred single-family houses, defined using the city centre pattern. It is a square area, 50 by 50 parcels (all occupied) with random buildings' orientations. Those examinations are focused on the economic and environmental issues. In this case, some building modernization variants, including **R**enewable **E**nergy **S**ources (RES) applications, are compared for two different localizations (accordingly Rzeszow and Szczecin). The economic assessments, as well as comparison of the **g**reen**h**ouse **g**asses (GHG) emissions, are performed. Thus, the economic and environmental profitability for the examined EC were analysed. The fourth case (section **4.3**) is focused on mapping various characteristics of the analysed area. The examined neighbourhood is defined using the street-grid pattern. It is a square zone, 50 by 50 parcels, including some empty ones; thus this EC consists of 2189 single-family houses. This example is analysed for two different localizations, accordingly Wroclaw and Bialystok. The obtained results are presented by means of maps, comparing energy- and environmental-related characteristics for variants before and after buildings' modernizations. Those type of studies allows establishing zones (within the examined neighbourhood) which are recommended to be modernized due to financial profitability and/or environmental protection. The last case (section **4.4**) is a non-uniform area, 50 by 80 parcels. The considered area was defined fully manually, using empty parcels;

the examined area consists of 1999 buildings and it is located in Warsaw. In this case, all types of available results obtained by means of the *TEAC* software are presented, to check the energy-, economic- and environmental profitability for some proposed modernizations.

The analyses of two more examples of residential ECs, performed by means of the *TEAC* software, are shown in chapter **5**. The both ECs are located in Lodz; the first one (section **5.1**) is a typical, small residential neighbourhood within the city district, while the second one (section **5.2**) can be considered as a wide-spread suburban area, where single-family houses are a majority of all buildings. Those examples might be considered as kind of case studies since they were defined based on the satellite photos of the selected areas. The both neighbourhoods are examined following the **E**nergy **F**lexible **B**uilding **C**luster (EFBC) concept – besides all the methods presented for the examples presented in the previous chapter, including some smart-metering techniques, are applied. The examined modernisation of the analysed clusters is based on highly energy-efficient buildings considered as a unity for energy accounting, providing the energy flexibility of the whole region. It is shown, that the EFBC approach, which assumed highly energy-efficient houses, which use of the RES, batteries systems, as well as smart-electricity management (including prosumer strategy) is arguably the most advanced approach to create sustainable urban areas.

Chapter **6** presents some conclusions and observations out of the performed study. The main conclusions are focused on the theses formulated at the beginning of the dissertation. Firstly, it is possible to use advanced energy simulations of a single building (performed by means of the software such as the *Energy Plus*) to be implemented for a whole considered residential areas. Secondly, the UBEM is a very comprehensive approach of urban planning, in which the EC concept fits perfectly – within the dissertation numerous ECs analyses were presented to follow-up the formulated statement. Thirdly, the main goal of the performed work was to develop a computational software, which is capable to perform energy-, economic- and environmental analyses of the Polish residential areas; thus, the *TEAC* software was developed and its' advisability and applicability for those type of comprehensive analyses of ECs were proven based on the presented results. Additionally, some supplementary conclusions were drawn.

Chapter **7** proposes some future researches – the most attention will be focused on the *TEAC* software improvements. Presently, the *TEAC* software should be considered as being in the beta stage, thus several actions are still necessary in order to consider it as a **R**eady **t**o **M**anufacture (RTM) software. The most essential improvements will be focused on the development of a **G**raphical **U**ser **I**nterface (GUI), as well as the addition of some upgrades, *e.g.* possibility to use **G**eographical **I**nformation **S**ystem (GIS).

This dissertation also includes eight appendices with some supplementary information about several issues presented in this work. It includes some data of the Polish residential sector (**Appendix 1**), as well as the assumptions used for performed studies of the Polish household (**Appendix 2**). The definition of RSFHs of Poland was introduced into the *Energy Plus* software – the buildings' computational models, as well as the applied HVAC installation schemas, are presented in **Appendix 3** and **Appendix 4**, accordingly. The applied schemas of the closest buildings' surrounding are shown in **Appendix 5**. **Appendix 6** includes the script of the defined NN, which was used for predicting heating demand. Some manuals on how to use the *TEAC* software are presented in **Appendix 7**. Additionally, some supplementary results are shown in **Appendix 8**.

SUMMARY IN POLISH (*STRESZCZENIE W JĘZYKU POLSKIM*)

Rozprawa doktorska zatytułowana *„Urban-scale energy modelling of some residential energy flexible buildings clusters in Poland”* (pol. "*Modelowanie energetyczne w skali urbanistycznej wybranych zespołów budynków mieszkalnych o adaptowalnych źródłach energii*) skupia się na zagadnieniach związanych z modelowaniem energetycznym obszarów miejskich (ang. *Urban Energy Modelling*) za pomocą autorskiego programu komputerowego *TEAC* (*Computational Tool for Energy Efficiency Analysis of an Energy Cluster)*. W rozprawie szczegółowo omówiono strukturę tego programu oraz algorytm działania jego poszczególnych modułów. Przeprowadzono także szereg analiz dotyczących aspektów energetycznych, ekonomicznych oraz środowiskowych obszarów mieszkalnych w Polsce. W rozprawie przedstawiono zastosowanie programu *TEAC* na przykładach tzw. Budowlanych Klastrów Energii (ang. *Building Energy Clusters*), które składać się mogą z setek domów jednorodzinnych. Każdy z zaprezentowanych przykładów przedstawia inny aspekt problematyki badawczej. Dodatkowo, w rozprawie omówiono zastosowanie programu *TEAC* do analizy rzeczywistych obszarów mieszkalnych zlokalizowanych w Łodzi.

Rozprawa składa się z 7 rozdziałów, spisu tabel i rysunków, jak również 8 załączników. Rozdział **1** zawiera wprowadzenie w tematykę niniejszej rozprawy. W rozdziale tym przedstawiono główne cele pracy oraz zdefiniowano tezy badawcze, o poniższym brzmieniu:

- możliwe jest wykorzystanie zaawansowanych symulacji energetycznych w celu prognozowania profili energetycznych pojedynczych budynków, jak również całych obszarów zabudowanych,
- koncepcja Klastra Energii (ang. *Energy Cluster*) jest właściwym podejściem pozwalającym poprawić profil energetyczny obszaru o zabudowie jednorodzinnej,
- możliwe jest prognozowanie zapotrzebowania na energię analizowanego obszaru mieszkalnego wykorzystując podstawowe dane go opisujące (zespół budynków).

Rozdział **2** przedstawia wstęp teoretyczny do tematyki niniejszej rozprawy, uwzględniając różne aspekty dotyczące modelowania energetycznego mieszkalnych obszarów miejskich (ang. *Urban Building Energy Modelling*). W p. **2.1** omówiono aktualny przegląd literatury dotyczący tematyki niniejszej rozprawy. W podrozdziałach **2.2** oraz **2.3** omówiono odpowiednio stan polskiego systemu elektroenergetycznego oraz sektora gospodarstw domowych. Strategie dotyczące poprawy efektywności energetycznej budynków zostały omówione w p. **2.4**, a tematyka ich rozwoju zgodnie z ideą zrównoważonego rozwoju (ang. *Sustainable Development*) została omówiona w p. **2.5**. Koncepcja Klastra Energii jako nowoczesnego podejścia do analizy obszarów składających się z obiektów budowalnych został opisany w p. **2.6**. Przegląd

aktualnie dostępnych programów komputerowych, które mogą być zastosowane do analiz energetycznych pojedynczych budynków, jak również całych obszarów miejskich przedstawiono w p. **2.7**. W kolejnej części (p. **2.8**) omówiono zastosowanie sztucznej inteligencji (ang. *Artificial Intelligence*) w analizach energetycznych budynków.

W rozdziale **3** opisano przyjęte założenia oraz wykonane analizy. Ta część pracy rozpoczyna się od prezentacji procedury wykorzystanej w ramach wykonanych analiz – procedurę tę przedstawiono w p. **3.1**. Wyróżnić w niej można czynności wstępne (m.in. przygotowanie danych wejściowych), których głównym celem było zdefiniowanie sztucznej sieci neuronowej (ang. *Neural Network*) wykorzystywanej do predykcji zapotrzebowania na energię grzewczą. Proces uczenia sieci został zaprezentowany w p. **3.6**. Czynności wstępne wykonane były tylko raz, natomiast właściwa analiza (tj. wszelkie obliczenia dot. Klastrów Energii) wykonywane są dla każdego analizowanego przypadku. Zebrane informacje oraz wyniki posłużyły jako dane wejściowe do opracowania programu *TEAC*, który został szczegółowo omówiony w p. **3.7**. Wykorzystanie programu *TEAC* do analiz obszaru mieszkalnego, stanowiącego Klaster Energii, został zaprezentowany na dwóch przykładach w p. **3.8**. Przegląd założeń, które zostały przyjęte podczas opracowywania programu *TEAC*, jak również na potrzeby przeprowadzonych w rozprawie analiz, zostały opisane w pozostałych częściach tego rozdziału. Założenia ogólne pracy opisano w p. **3.2**, natomiast wykorzystane dane klimatyczne omówiono w p. **3.3**. Opis polskich referencyjnych domów jednorodzinnych (ang. *Representative Single-Family Houses*) zaprezentowano w p. **3.4**, a opis proponowanych modernizacji tych budynków w p. **3.5**.

Rozdział **4** poświęcono przedstawieniu przykładów obliczeniowych dotyczących Klastrów Energii obszarów mieszkalnych, wykonanych za pomocą programu *TEAC*. Zaprezentowane przykłady miały na celu pokazanie możliwości opracowanego programu; każdy z nich dotyczył innej tematyki badawczej. Pierwszy przykład (p. **4.1**) dotyczył obszaru 2500 (50 x 50) działek, z których każda działka była zajęta; analizowany obszar składał się z 2500 domów jednorodzinnych. Dobór budynków był losowy – dotyczyło to zarówno typu budynku, jak również ich orientacji. Ten przykład prezentował wyniki dot. zużycia energii analizowanego Klastra Energii, przede wszystkim przy użyciu krzywych obciążenia sieci (ang. *Load Duration Curves*). Tego typu analizy pozwalają na sprawdzenie, a następnie dobór modernizacji budowlanych, które prowadzą do zwiększenia bezpieczeństwa lokalnej sieci elektroenergetycznej. Rozpatrując obszar mieszkalny jako Klaster Energii możliwe jest zarządzanie obciążeniami szczytowymi, jak również lepsze zarządzanie zapotrzebowaniem na energię tego obszaru. Drugi przykład (p. **4.2**) dotyczy Klastra Energii składającego się z 2500 domów jednorodzinnych, jest to osiedle zdefiniowane na obszarze 50 na 50 działek, o strukturze miasta z wyraźnym centrum. Analizy w ramach tego przykładu skupione są na aspektach ekonomicznych oraz środowiskowych, możliwych do oszacowania przy użyciu programu *TEAC*. W ramach analizy porównano dwie lokalizacje w Polsce, Rzeszów i Szczecin, a wśród rozpatrywanych modernizacji przeanalizowano m.in. wykorzystanie Odnawialnych Źródeł Energii. Przeprowadzona analiza ekonomiczna zakładała weryfikację opłacalności finansowej proponowanych wariantów modernizacyjnych dla analizowanego obszaru (opis wykorzystanych technik znajduje się w podrozdziałach **2.5** oraz **3.7**). Przeprowadzona analiza środowiskowa obejmuje oszacowanie emisji gazów cieplarnianych (ang. *greenhouse gasses*), wynikających z zapotrzebowania na energię rozpatrywanego klastra. Zweryfikowano, że oprogramowanie *TEAC* jest odpowiednim narzędziem do analiz ekonomicznych i ekologicznych obszarów typu Klaster Energii. Trzeci przykład (p. **4.3**) przedstawia wyniki analiz w formie map (tzw. *mapping*). Rozpatrywany obszar jest Klastrem Energii, składającym się z 2189 domów jednorodzinnych; analizowane osiedle obejmuje obszar 50 na 50 działek (założono, że niektóre z nich są puste) i zostało zdefiniowane korzystając z predefiniowanej siatki ulic. Zestawiono wyniki uzyskane dla dwóch lokalizacji, odpowiednio Wrocławia i Białegostoku. Zaprezentowane mapy przedstawiają wyniki analizy energetycznej i środowiskowej badanego obszaru, porównując stan przed i po modernizacji budynków wchodzących w skład analizowanego osiedla. Tego typu analizy posłużyć mogą do wyznaczenia stref analizowanego klastra, które wykazują wysoki potencjał poprawy efektywności energetycznej. Dodatkowo, możliwe jest wyznaczenie obszarów, dla których proponowane modernizacje są najkorzystniejsze finansowo, jak również pod kątem ochrony środowiska (redukcji emisji gazów cieplarnianych). Ostatni czwarty przykład (p. **4.4**) jest osiedlem o kształcie niejednorodnym, zlokalizowanym w Warszawie. Analizowane osiedle wpisane jest w obszar 50 na 80 działek, z których tylko 1999 jest zajętych. W tym przykładzie wykonano kompleksową analizę Klastra Energii przy użyciu programu *TEAC*. Dzięki analizie tego typu możliwa jest kompleksowa ocena rozpatrywanego osiedla domów jednorodzinnych, sprawdzająca aspekty energetyczne, środowiskowe, jak również ekonomiczne.

W rozdziale **5** rozprawy przedstawiono wyniki dla dwóch rzeczywistych osiedli mieszkaniowych, zlokalizowanych w Łodzi, o których założono, że stanowią Klastry Energii. Analizowane klastry rozpatrywać można jako „*studium przypadku*”, gdyż ich definicja opierała się na zdjęciach satelitarnych rzeczywistych obszarów mieszkalnych. Pierwszy z nich (p. **5.1**) jest małym fragmentem typowej dzielnicy mieszkaniowej, składającej się z domów jednorodzinnych, natomiast drugi (p. **5.2**) jest rozległym obszarem podmiejskim, gdzie budynki mieszkalne (przede wszystkich domy jednorodzinne) stanowią zdecydowaną większość zabudowy lokalnej. Oba rozpatrywane Klastry Energii analizowano pod kątem ich transformacji w obszary wysoce efektywne i elastyczne energetycznie, umożliwiając częściową niezależność energetyczną (ang. *Energy Flexible Building Cluster*). W ramach przeprowadzonych analiz zastosowano wszystkie strategie omówione w rozdziale **4**. Dodatkowo, założono zastosowanie metody pozwalającej na zarządzanie zapotrzebowaniem na energię, wykorzystując w tym celu magazyny energii elektrycznej. Ponadto, stosując metody inteligentnego rozliczania zużycia energii elektrycznej (ang. *smart-metering*) możliwe jest bardziej efektywne i korzystniejsze finansowo zarządzanie zapotrzebowaniem energii analizowanych klastrów. Rozwój tego typu obszarów, składających się z wysoce energooszczędnych domów, wykorzystujących lokalną produkcję energii z OZE są niezwykle istotne dla rozwoju zrównoważonych obszarów miejskich. Wykazano, że program *TEAC* umożliwia przeprowadzenie tego typu analiz dla rzeczywistych obszarów mieszkalnych w Polsce.

Rozdział **6** zawiera wnioski i podsumowanie z analiz przeprowadzonych w rozprawie. Główne podsumowanie odnosi się do tez postawionych we wstępie pracy. Po pierwsze wykazano, że możliwe i słuszne jest wykorzystanie zaawansowanych programów symulacyjnych do analiz energetycznych pojedynczych budynków, jak również grupy obiektów mieszkalnych. Po drugie, przeprowadzono szereg analiz potwierdzających, że modelowanie energetycznego zabudowanych obszarów miejskich jest zagadnieniem niezwykle złożonym, które z powodzeniem można stosować przy analizie Klastrów Energii. Po trzecie, na potrzeby niniejszej pracy opracowano program *TEAC*, służący do analiz Klastrów Energii, składających się z osiedli mieszkalnych, w skład których wchodzą polskie reprezentatywne domy jednorodzinne. Program *TEAC* oraz wszystkie jego możliwości zostały sprawdzone w ramach niniejszej rozprawy wykazując, iż jest on narzędziem odpowiednim do analiz obszarów mieszkalnych w Polsce. Dodatkowo, podczas wykonywania opisanych analiz wyciągnięto inne ciekawe wnioski, które zostały podsumowane w tym rozdziale.

Rozdział **7** zawiera krótki opis planowanych przyszłych badań. Większość z nich skupia się na ulepszaniu programu *TEAC*, tak aby możliwe było jego rozpowszechnienie. Wśród najważniejszych zadań wymienić należy wprowadzenie graficznego interfejsu programu (ang. *Graphical User Interface*), jak również dodanie modułu pozwalającego na korzystanie z systemu informacji geograficznej GIS (ang. *Geographical Information System*).

Rozprawa zawiera 8 załączników z szeregiem dodatkowych informacji. W **Załączniku 1** zestawiono podstawowe informacje dot. analizowanych referencyjnych domów jednorodzinnych w Polsce. W **Załączniku 2** założenia wykorzystane przy definiowaniu budynków poddanych analizie w ramach niniejszej rozprawy. Modele numeryczne domów jednorodzinnych zostały zdefiniowane w programie *Energy Plus*; zawiera je **Załącznik 3** oraz **Załącznik 4**. Przyjęte schematy najbliższego otoczenia analizowanych budynków (mające na celu uwzględnienie wpływu zacienienia) zostały pokazane w **Załączniku 5**. W **Załączniku 6** podano skrypt zdefiniowanej sieci neuronowej, służącej do przewidywania zapotrzebowania na energię cieplną budynku jednorodzinnego, wchodzącego w skład Klastra Energii.

W **Załączniku 7** pokazano, w jaki sposób zdefiniowano przykładowe obszary typu Klaster Energii (omówione w p. **3.8**) przy użyciu programu *TEAC*. Ponadto, w **Załączniku 8** podano dodatkowe wyniki dla przykładów omówionych w rozdziale **4**.

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NOMENCLATURE

SYMBOLS

α – altitude angle [deg]

β – tilt angle [deg]

γ – azimuth angle [deg]

δ – declination [deg]

ΔO_N – annual savings [PLN/a]

$\Delta\theta$ – temperature gradient [K/m]

η_{PU} – power unit efficiency [%]

η_{PV} – PV efficiency [%]

θ_a – air temperature [°C, K]

θ_e – reference outdoor temperature [°C, K]

θ_{mr} – mean radiant temperature [°C, K]

ρ_o – surface reflectance [-]

φ – latitude [deg]

ω – solar angle [deg]

B_F – fuel consumption [g, kg, t]

B_{PV} – PV width [m]

$C_G(\tau)$ – global cost (corresponding to calculation period τ) [PLN]

C_I – initial investment costs [PLN]

C_O – operation costs, including running and periodic expenses [PLN]

E – emission of substance (gas) [g, kg, t]

E_C – electricity consumption [kWh]

E_{RES} – electricity produced out of local RES systems [kWh]

H_C – heating consumption [kWh]

I_c – the hourly solar irradiation [W/m^2]

I_{cl} – clothing insulation [clo, m^{2}K/W]

k_D – factor expressing losses during electricity distribution [-]

k_S – the share of a different fuel type used in the national electricity system [%]

L_{PV} – PV length [m]

M –activity level [W/m^2, Met]

N_U – total investments [PLN]

p_a – air humidity [%]

R – thermal resistance [m^2K/W]

R^2 – multiple correlation coefficient

$R_1, R_2, \ldots, R_n$ – thermal resistances of each layer [m^2K/W]

R_b – correction factor for beam radiation [-]

R_d – correction factor for diffuse radiation [-]

R_{DR} – discount rate [%]

R_r – correction factor for reflected radiation [-]

R_{se} – external surface resistance [m^2K/W]

R_{si} – internal surface resistance [m^2K/W]

R_T – total thermal resistance [m^2K/W]

t, τ – time period considered for the calculations, analyses [s, min, h, y]

q – heat flux density [W/m^2]

Q_p – primary energy demand [kWh/m^2a]

U – thermal transmittance [W/m^2K]

v_a – relative air velocity [m/s]

$V_{f,\tau}$ – final or residual value [PLN]

w_F – emission factor per used fuel [g/Mg]

X_A – horizontal number of parcels of the analysed area in the *TEAC* software [-]

Y_A – vertical number of parcels of the analysed area in the *TEAC* software [-]

ABBREVIATIONS AND ACRONYMS

AEB – Energy Audit for Building

AEE – Energy Efficiency Audit

AI – Artificial Intelligence

AL – Appliances & Lighting

ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers

BAS – Building Automation System

BBN – in Polish: *Biuro Bezpieczeństwa Narodowego* (the National Security Bureau of Poland)

BC – Building Cluster

BEC – Building Energy Cluster

BEMPs – Building Energy Modelling Programs

BEMS – Building Energy Management System

BIPV – Building Integrated Photovoltaic

BIWT – Building Integrated Wind Turbines

BMS – Building Management System

BREEAM – Building Research Establishment Environmental Assessment Method

BREHOMES – Building Research Establishment Housing Model for Energy Studies

BSM – Building-Stock Model

CDA – Conditional Demand Analysis

CDEM – Community Domestic Energy Model

CE – Circular Economy

CHM – Cambridge Housing Model

CO_2 – Carbon Dioxide

COP – Coefficient of Performance

CREEM – Canadian Residential Energy End-use Model

CV – Coefficient of Variation

DBRT – Design-Based Rating Tools

DBT – Dry-bulb Temperature

DECM – Domestic Energy and Carbon Model

DGNB – in German: *Deutsche Gesellschaft für Nachhaltiges Bauen*

DGO – Distribution Grid Operators

DHW – Domestic Hot Water

DOE – the U.S. Department of Energy

DSM – Demand Side Management

EBC – Energy Building Certificates

EC – Energy Cluster

ECCABS – Energy, Carbon and Cost Assessment for Building Stocks

EEA – European Environment Agency

EEM – Energy Efficiency Measure

EFB – Energy Flexible Building

EFBC – Energy Flexible Building Cluster

EFUA – Energy Flexible Urban Areas

EHPE – Efficiency House Plus with Electro-mobility

EPBD – Energy Performance of Building’s Directive

EPC – Energy Performance Certificate

EPISCOPE – Energy Performance Indicator Tracking Schemes for the Continuous Optimisation of Refurbishment Processes in European Housing Stocks

EPS – Expanded Polystyrene Styrofoam

EU – the European Union

FBNN – Feed Backward Neural Network

FFNN – Feed Forward Neural Network

GA – Genetic Algorithms

GHG – Greenhouse Gasses

GHP – Geothermal Heat Pump

GIS – Geographical Information System

GUI – Graphical User Interface

GUS – in Polish: *Główny Urząd Statystyczny* (the Central Statistical Office)

HAWT – Horizontal-axis Wind Turbines

HVAC – Heating, Ventilation & Air Conditioning system

IBP – Fraunhofer Institute for Building Physics

idf – Intermediate Data Format

IEA – International Energy Agency

IEE – Intelligent Energy Europe

IEQ – Indoor Environment Quality

IRENA – International Renewable Energy Agency

IRM – Isotropic Radiation Model

KOBiZE – in Polish: *Krajowy Osrodek Bilansowania i Zarzadzania Energiami*

LCA – Life Cycle Assessment

LCC – Life Cycle Cost

LDC – Load Duration Curve

LEAP – Long-range Energy Alternatives Planning

LEED – Leadership in Energy and Environmental Design

LM – the *Lavenberg-Marquardt* method

LW-DAB – Local-Weather Distributed Adjacency Blocks

MAED-2 – Model for Analysis of Energy Demand

ML – Machine Learning

MW – Mineral Wool

NABERS – National Australian Built Environmental Rating System

NAPE – in Polish: *Narodowa Agencja Poszanowania Energii* (the National Energy Conservation Agency)

NCV – Net Calorific Value

NEMS – the National Energy Modelling System

NN – Neural Network

NO_x – Nitrogen Oxides

NPV – Net Present Value

NREL – National Renewable Energy Laboratory

nZEB – net Zero-Energy Building

NZEB – Nearly Zero-Energy Building

OWEOB – in Polish: *Ośrodek Wdrożeń Ekonomiczno-Organizacyjnych Budownictwa*

PC – Pilot Cluster

PCM – Phase Change Material

PEB – Plus-Energy Building

PIR – Polyisocyanurate

PM – Particulate Matters

$PM_{2.5}$ – Particulate Matters with particles fraction diameters up to 2.5µm

PM_{10} – Particulate Matters with particles fraction diameters up to 10µm

PMV – Predicted Mean Vote

PPD – Predicted Percentage of Dissatisfied

PRT – Performance Rating Tools

PUR – Polyurethane foam

PV – Photovoltaic

PVT – Photovoltaic Thermal hybrid

REEPS – Residential End-use Energy Planning System

REM – Regional Engineering Model

RES – Renewable Energy Sources

RMSE – Root-Mean-Square Error

RSFH – Representative Single-Family House

RTM – Ready to Manufacture programme

SB – Smart Buildings

SC – Space Cooling

SD – Sustainable Development

SH – Space Heating

SHGC – Solar Heat Gain Coefficient

SO_2 – Sulphur Dioxide

SPBT – Simple Pay-Back Time

SRT – Sustainable Rating Tools

SSE – Sum of Square Errors

SW – Solar Window

SUD – Sustainable Urban Development

TABULA – Typology Approach for Building Stock Energy Assessment

TEAC – Tool for Energy Efficiency Analyses of an Energy Cluster

TMY – Typical Meteorological Year

TRY – Test Reference Year

UBEM – Urban Building Energy Modelling

UEI – Urban Energy Interface

UEM - Urban Energy Maps / Urban Energy Modelling

UHI – Urban Heat Island

UWE – Urban Wind Energy

UNFCCC – United Nations Framework Convention on Climate Change

USEM – Urban-Scale Energy Modelling

VAWT – Vertical-axis Wind Turbines

WCED – the World Commission on Environmental and Development

WTF – Wind Turbines Farm

XPS – Extruded Polystyrene Styrofoam

1. INTRODUCTION

In this chapter, an introduction to the doctoral thesis was presented. The dissertation is focused on the global trend aimed at the improvement of energy efficiency for urban areas. Performed work fits perfectly with the Energy Clusters concept, which is a novel model of complex, energy-related analysis of regions. Considering a lack of Energy Clusters' national policy and regulations it is a great opportunity to perform researches within the proposed topic.

Today, a vision of humanity without energy is impermissible. Energy might be defined in a wide range of definitions, but in fact, electricity and heat are crucial for the present civilisation. Moreover, people spend a majority of their lives indoor – at the beginning of human evolution, caves with bonfire were natural shelters, while now we are living in comfortable apartments with many facilities. The energy, in general, is essential for comfortable standards of living. Heat allows maintaining appropriate temperature indoor during adverse outside climate conditions while electricity ensures facilities, equipment and lighting systems operation. The concept of energy within households is comprehensively analysed, due to the present needs and nature of human existence.

Nowadays, the policy related to energy efficiency and environmental protection is global. Each country chase towards sustainability under a set of specific regulations and guidelines. Over the last two decades, the world's total primary energy consumption has raised by 49% (throughout all economic sectors: industrial, buildings, transport and agricultural), with an average annual growth of approx. 2% [210]. The amount of consumed energy and emitted pollutions are outcomes of multiple factors related to the building sector. Buildings (both residential and commercial) are still the major part of total energy consumption globally [408] – typically buildings respond for approx. one-third of the world's total energy consumption (see **Figure 1.1**), respectively about 26% in the **E**uropean **U**nion (EU) [408]. National energy consumption share of building sector varies depending on the conditions of each country – it can reach up to 50%. The amount of energy consumption is directly related to buildings energy characteristics and their localizations. Additionally, buildings can consume up to 75% of the total primary energy in cities [418]. The emissions are dependent on the amount of consumed energy as well as on used fuels during the process of energy production. Both, energy and emission analyses within the household sector are a meaningful and valid field of civil engineering researches. The residential sector presents a great possibility for energy consumption and greenhouse gases emission (especially CO_2) emission reduction, by applying proper energy-saving policies.

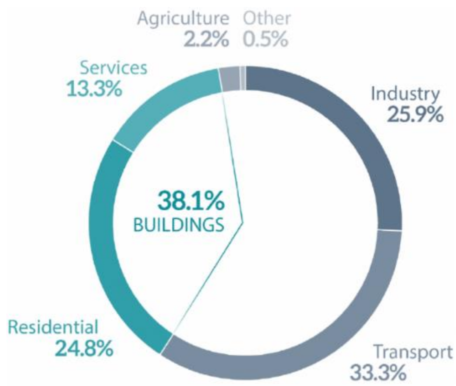


Figure 1.1. *Energy consumption by sectors in the EU-28 in 2014 (source: [408])*

National energy supply security is crucial for the proper operation and economic development of every country. Global energy consumption is characterized by constant growth caused by a significant increment in industrial and urban sector development. The rapid increase of the world population is also a driving component in total energy consumption – it is foreseen, that global energy demand might increase by over 50% within the next dozens of years [370]. In **Figure 1.2** the estimated world-wide energy consumption and earth population were presented – the mutual correlation between them can be observed. As a consequence of a constantly increasing energy demand, environmental issues are becoming more apparent.

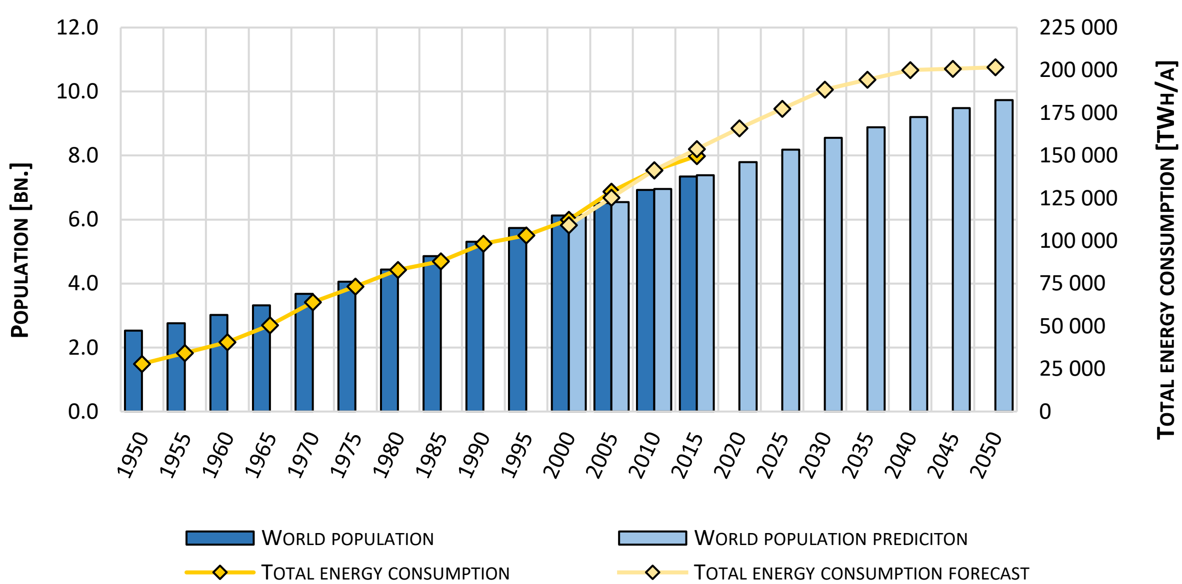


Figure 1.2. *Comparison of the world population with total energy consumption – statistic & forecasts until 2050 (own study, source: [322], [395], [426])*

High demand for new residential and commercial buildings is observed due to the increasing global population, thus civil engineering is presently in a golden era because of numerous investments. Within the building sector, residential one is a major part and their number will constantly increase parallel to the rising population. According to [298], a global amount of households will increase up to 3.2 billion in 2050, compared with 2.2 billion reported in 2015. It is crucial to focus on buildings energy efficiency to counter, or at least inhibit, energy consumption growth within residential. New and renovated buildings should be characterized by high thermal parameters of building enclosure as well as highly efficient installations.

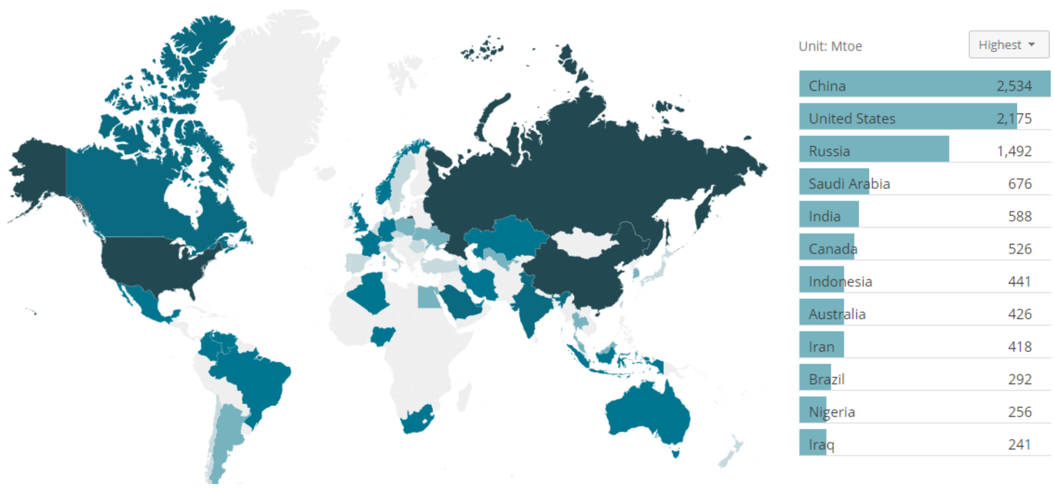


Figure 1.3. *Energy consumption breakdown by country – 2018 (source: [376])*

We do really live in an age of fossil fuels – most of the used energy probably coming from non-renewable sources like coal, oil or natural gas. The biggest energy consumer is China, followed by the United States and Russia (**Figure 1.3**). The energy production is constantly evolving, increasing **R**enewable **E**nergy **S**ources (RES) usage. According to [306], at the end of 2016 approx. 24.5% of produced electricity came out of renewables. According to IRENA's (**I**nternational **R**enewable **En**ergy **A**gency) [387] predictions, in 2050 we might expect a global energy system transformation, with 86% of power demand catered by renewables (**Figure 1.5**) – with main assets in solar and wind energy [298]. According to the newest publications [305], even further energy independence is possible. Research results presented at the annual **U**nited **N**ations **F**ramework **C**onvention on **C**limate **C**hange (UNFCCC) conference not only prove, that zero-emissions energy production is possible sooner than we were expecting, but also that it is a cost-effective approach. The global power sector will at least double its size by 2050 and would be deeply transformed. The ongoing energy system shift, assuming switch from traditional to decentralized renewable energy sources based is a challenge for engineers, researchers and scientists. Therefore, in the nearest future, it is crucial to encourage the uptake of renewables into urban built environments. Also, an increase in renewables applications' popularity will favour dispersed energy production, resulting in a more stable national grid. Moreover, RES usage will simultaneously increase the use of storage systems, allowing to use of overproduced energy later, when it is necessary. In the upcoming future, the national grid will be characterized by greater flexibility, suitable for significant shares of renewables usage.

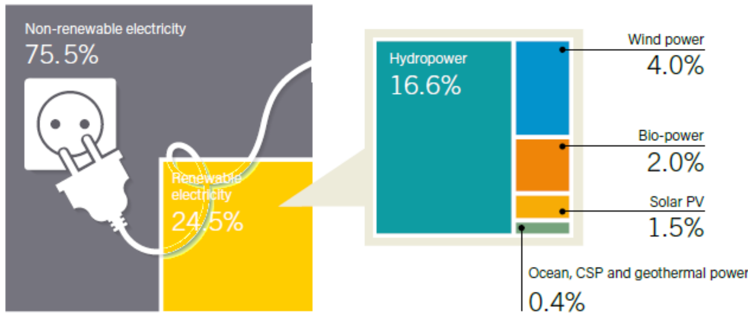


Figure 1.4. *Estimated renewable energy share of global electricity production – 2016 (source: [306])*

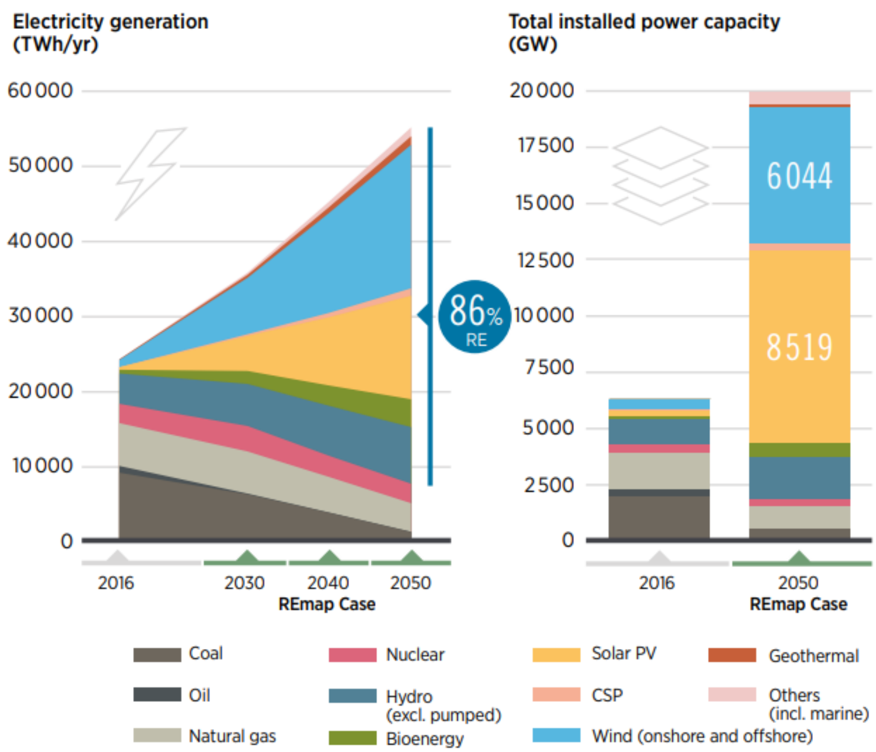


Figure 1.5. *Electricity generation mix and power generation installed capacity by fuel, 2016-2050 (source: [298])*

The energy system transformation is also caused by the constant pursuit of air quality improvement. It is well known, most of the low-emission came from combustion processes, usually observed in the residential sector. According to the **E**uropean **E**nvironment **A**gency (EEA) [408], low-emission is both, environmental and healthiness harmful. Counter-measure is quite obvious – there is a necessity of heating stoves modernizations as well as the implementation of RES within energy production.

The attentiveness should be also pointed to energy demand due to its' non-uniformity time distribution. The energy distribution should work constantly and assure a balanced energy supply depending on present demand. Unfortunately, energy demand varies according to time of the day, as well as a time of the year – it is characterized by high daily amplitudes of the momentary demand and their occurrences distribution. Monitor and energy consumption forecast the national power system is crucial to ensure the correct operating of the system.

One of the biggest challenges is to form a proper energy demand distribution of the buildings sector without a noticeable impact on the resident's lives and behaviours. Nowadays, it is possible to successfully apply RES or advanced **D**emand **S**ide **M**anagement techniques (DSM) to buildings. In particular, energy efficiency is the priority for new buildings as well as retrofitted ones. Households are typically distributed within zones constituting neighbourhoods – it is highly promising to analyse whole areas providing local grid management. The approach focused on energy-related analyses of whole areas is a key factor for local sustainability – it is promising to implement environmentally friendly solutions for residential regions. The above-mentioned method results in the improvement of local grid safety as well as is pro-environmental. It is highly promising to analyse whole residential areas collectively, in order to improve local energy and environmental situation.

1.1. RESEARCH MOTIVATION

Today, every highly developed country stands in front of the necessity of energy efficiency transformation. According to the long term policy of the European Union, the main focus is set at two targets: energy consumption reduction simultaneously with minimalizing the greenhouse gas emissions. Focusing on households, there is a need for deep thermo-renovation of buildings, but also an obligation in RES usage to accomplish the above-mentioned targets. Nowadays, during the time of the fastest technology development in history, the modern and high-tech point of view on the national plans concerning the improvement of energy efficiency is obligatory. Thus, the forthcoming plans and policies should involve advanced strategies of buildings modernizations.

In Poland, a leading way of building energy-related calculations is based on **E**nergy **B**uilding **C**ertificates (EBC). The calculations are based on monthly averaged parameters such as external climate conditions data or installations efficiency, which is a huge simplification of building's energy characterizations. Analyses performed using the monthly balance method can be considered only as an estimation of proposed modernizations' effects. Also, due to constraints of the method, it cannot be used to study many advanced techniques application. The novel approach of buildings energy-related analyses are based on advanced computer simulations, performed with at most an hourly calculation step with detailed weather data usage. Those kinds of energy-related analyses allow us to fully understand examined projects, as well as to select appropriate modification out of proposed modernizations.

Residential buildings are usually a major part of a large-scale built environment establishing a city-district. Energy-related analyses of the household sector should be pursued using a holistic approach – whole area analyses. Those type of energy-related analyses allows to obtain a realistic assessment for some proposed modernizations. Additionally, those kinds of analyses are in accordance with an **E**nergy **C**luster (EC) concept – a novel approach to residential area considerations.

The energy condition of the Polish household sector is unsatisfactory – there is a high necessity of deep, national thermal renovation as well as revisions in the national power system. Interestingly, single-family houses are major energy consumers in Poland, while improving their energy efficiency is relatively easy. It seems like there is a huge potential within the Polish household sector for national improvement towards sustainability. Moreover, single-family houses are typically placed within residential areas which are perfect for practical application of the EC concept.

The main motivation of the dissertation was to create a multi-criteria computer analytic tool for residential areas analyses, containing all the aspects discussed above. In fact, the developed software allows performing energy, environmental and economy analyses of the Polish household sector, based on detailed input and output datasets. There is no such software available to analyse Polish buildings stock which might be an extremely useful tool for national energy analyses and load forecasting.

1.2. PROBLEM STATEMENT AND AIM OF THE THESIS

Studying the energy consumption of the urban area requires analyses of energy performance within the household sector. Building energy efficiency and RES applications, resulting in building stock energetic improvement, is a basics for an EC definition. The EC concept seems to be a promising approach toward the development of sustainable and energy-independent urban areas. The above-mentioned keynote might be achieved using an innovative computer tool named *TEAC*, developed in order to perform energy, economic and environmental analyses of the investigated area.

The aim of this thesis is a multi-criteria analysis of the urban area by means of a numerical approach using computer simulations. The main goal of the performed study was to inquire, whether it is possible and valid to create a simple computer software, appropriate for urban area analyses in pursuance towards sustainability of the region. The computer **T**ool for **E**nergy Efficiency **A**nalyses of an Energy **C**luster (*TEAC* software) software is based on Polish representative single-family houses computer models. The research contains forecasting of power demand and energy consumption, as well as greenhouse-gases emission within a residential area, by means of **A**rtificial **I**ntelligence (AI) application. All in all, the *TEAC* software might be used as a helpful tool for contributing to the development of ecology and energy efficiency policy. The developed tool might be used by the local territory agencies to perform province-, commune-, city- or neighbourhood- scale energy analyses. Moreover, the tool can be used for approximate prediction of the energy demand for the city-states area of Poland.

The performed dissertation is following three main theses, as follows:

1. advanced energy computer simulations can be used for detail predictions and analyses of energy demand profiles for a single building as well as whole residential areas;
2. the Energy Cluster concept is an appropriate and promising approach toward improvement in the energy economy as well as the development of sustainable and energy-independent urban areas;
3. it is possible to develop a computational software, which is capable to perform energy, economic and environmental analyses of the Polish residential stock areas, based on buildings parameters, their mutual influences and interactions, as well as climate data.

1.3. CONTENT OF THE THESIS

The thesis consists of 6 chapters, bibliography, eight attachments as well as lists of tables, figures and symbols.

In chapter **1** the general introduction has presented the general overview of the thesis, research motivation, purposes and scope of the dissertation.

Chapter **2**, consisting of 8 sections, formulates a theoretical background related to the residential area's energy analyses. This part of the dissertation includes a description of parameters highly related to buildings' energy consumption, especially in Poland. The content includes notably a detailed description of methodologies used for energy management in urban areas (section **2.1**), an overview of the electrical energy system of Poland (section **2.2**) and the Polish residential building stock (section **2.3**) as well as a review of methods used for the improvement of buildings' energy efficiency (section **2.4**). Furthermore, the buildings' sustainability was discussed in section **2.5**, while in section **2.6** a detailed overview of the EC concept was presented. Additionally, an approach to urban energy analyses using simulation tools is described in section **2.7**. Finally, an application of the artificial neural network for buildings' energy-related analyses was overviewed (section **2.8**).

Chapter **3**, consisting of 8 sections, is focused on the presentation of the study description and performed assumptions. Notably, this part of the dissertation includes applied procedure description (section **3.1**), list of main assumptions necessary for the analysis (section **3.2**), boundary conditions related to exterior climate (section **3.3**) as well as used buildings out of Polish residential sector (section **3.4**). Additionally, a list of performed modernization variants of the analysed building is presented in section **3.5**. In section **3.6**, the completed NN training process was shown. Finally, section **3.7** is focused on an overview of modules constituting the *TEAC* software – home-developed computational tool for urban-scale, energy, economic and environmental analyses, while in section **3.8** some simple examples of its application were shown.

Chapter **4** is dedicated to a comprehensive presentation on more complex applications of the *TEAC* software. To that end, 5 different scenarios of residential areas were presented (each of them formed of hundreds of single-family houses). The analysed zones are considered as Building Energy Clusters; performed studies are focused on energy, economic and environmental aspects.

In chapter **5** some case-study analyses are shown. Two examples of residential neighbourhoods located in Lodz are examined using the *TEAC* software. The performed studies carried out the potential of transforming the analysed residential areas into Energy Flexible Building Clusters. Also, some smart metering techniques are discussed by means of electricity billings calculations.

Chapter **6** summarizes all conclusions and observations obtained during the studies. Comments and thoughts consequent from the performed dissertation have been presented. Additionally, the results of the executed analyses were summarized. Moreover, possibilities of development of the *TEAC* software have been pointed out.

Finally, in chapter **7**, prospective future researches are proposed. This part of the work includes conceptions and ideas emerged after performed studies. Most of them are related to the further development of the *TEAC* software in order to make it accessible and available to all the interests.

2. THEORETICAL BACKGROUND

Nowadays, environmental protection is one of the main political and research topics all over the world. Many international directives concern the reduction of **g**reen**h**ouse **g**as emission (GHG) as a major goal towards required for ecological-friendly development. Long-term climate targets (*going climate-neutral by 2050* plan) set by the EU assuming carbon-free continent with reduction of GHG emissions by approx. 90 % in 2050 compared to 1990. In the EU, the building sector is responsible for approx. 40 % of energy consumption and 36 % of CO_2 emissions [335]. Modernizations are necessary for all economic sectors (see **Figure 2.1**), but it seems like buildings are crucial for effective climate policy.

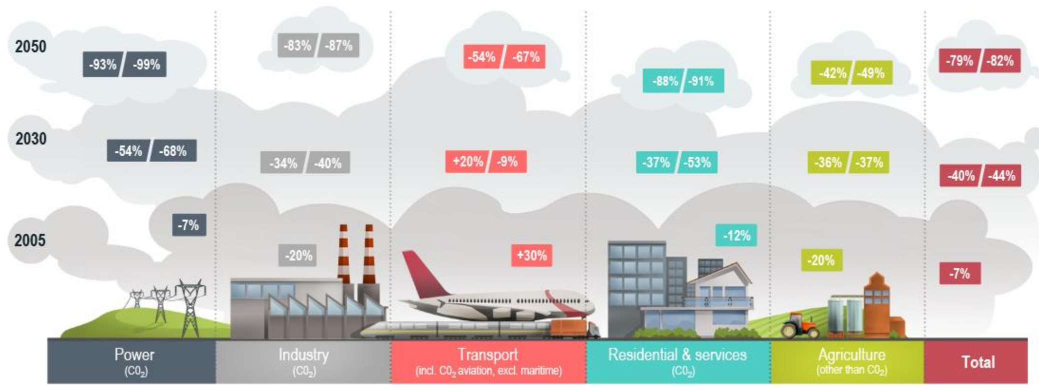


Figure 2.1. *European Union strategy for low emission Europe - 2050 long-term strategy (source: [290], [407])*

Due to climate change, constantly growing energy prices and energy supply & demand, there is a high interest in researches related to overall energy production and consumption process. The energy consumption by main economic sectors, omitting residential sector, is well understood due to their self-interest and knowledge in reducing energy consumption. The residential sector is still an undefined energy sink, due to reasons like size, geometry and envelopes' thermal parameters variety, diversity of occupants behaviours and needs, as well as limitations in acquiring energy consumption data. There is a highly-needed interest in understanding a detailed energy-profile of the residential sector in order to develop sustainable, environmental-friendly building stocks.

In this chapter, the overview of the energy consumption within the buildings sector was presented. Handbooks, guidebooks, scientific articles, specialized reports, public statistic databases and many web sources were investigated within the State-of-the-art review. An urban energy efficiency improvement starts with a single building – only by the refurbishment of buildings constituting analysed area, it is possible to create energy-efficient and sustainable cities. Additionally, a zone, in which an energy-efficient modernization was applied, might be considered as a basis for establishing an **E**nergy **C**luster (EC). Taking into account the complexity of urban areas analyses it is necessary to use computer simulations to study issues related to the energy profile of residential areas. Summarizing, this section is focused on methods of smart city design. Furthermore, some sections are summarized with concluding remarks.

2.1. METHODOLOGIES OF ENERGY MANAGEMENT IN URBAN AREAS – REVIEW

Buildings can consist of up to 75 % of total energy consumption in cities [418]. Residential energy models may focus on a different level/scale of analysis, starting with a thermal zone, building, neighbourhood, city, state, region, or even whole country. Methodologies used for the energy performance evaluation of a single building were already been discussed in numerous studies [17], [75], [130]. It is essential to shift from building-scale analyses to the neighbourhood-scale in order to match the scale of demand created by distributed energy systems (*e.g.* energy hubs) [173], [211], [212]. To perform more detailed and complex investigations of residential building stocks, a comprehensive set of input parameters is required – the accurate assumptions are crucial for the improvement of a model definition process as well as providing suitable results. The residential stock data is usually published by governments with cooperation with energy providers. Those types of data are usually estimations, encumbered with inaccuracy related to the account of unreported energy generation (including on-site energy production). A more detailed data might be obtained from the billing records of energy suppliers – however, it is limited due to consumers privacy regulations. Nevertheless, the energy consumption data is not enough to model a residential area – the correlation with buildings parameters and occupants behaviour records is necessary. Only when a high-quality, detailed data regarding the analysed area is available, an effective process of defining a residential stock model is possible.

Residential stock models might be successfully used to evaluate the environmental and socio-economic impacts of building modernizations [40]. The uncertainty related to researches and analyses of a single building is a frequent concern [162], [167], [266], let alone the whole residential stock models –it is a very complex undertaking to model building areas consisting of various buildings. Unfortunately, each model has some limitations and uncertainties – it is crucial to match the defined model accuracy with the analysed case. After all, building stock models analyses can play a meaningful role in the decision-making process. The main limitations of existing housing stock models can be classified referring to the accuracy of defined models (comparing with real data), difficulty in data collection (used during model development) and computational cost (the more complex model the longer simulation time).

Nevertheless, **U**rban **B**uilding **E**nergy **M**odels (UBEM) can be a helpful tool, applied to support cities energy management as well as the development of urban sustainability.

Typically, two methods of building analyses are used for either individual or city-scale studies: data-driven [143], [164] or physical models [160]. Data-driven models are capable to identify operation-related problems but it is difficult to use them for building retrofitting analyses. On the other hand, physical models, which investigate heat and mass flow in and around buildings, are capable to analyse operational energy use, simultaneously including the impact of indoor and outdoor climate conditions to evaluate buildings retrofitting.

According to [251], presently used techniques to perform energy-related analyses of residential stocks can be grouped into 2 main types: '*top-down*' and '*bottom-up*' (see **Figure 2.2**). Generally speaking, '*top-down'* models characterize entire housing sector with an estimation of a total residential sector energy consumption, while, the '*bottom-up*' models use a calculation of energy consumption of individual or groups of houses to extrapolate these results to the analysed region.

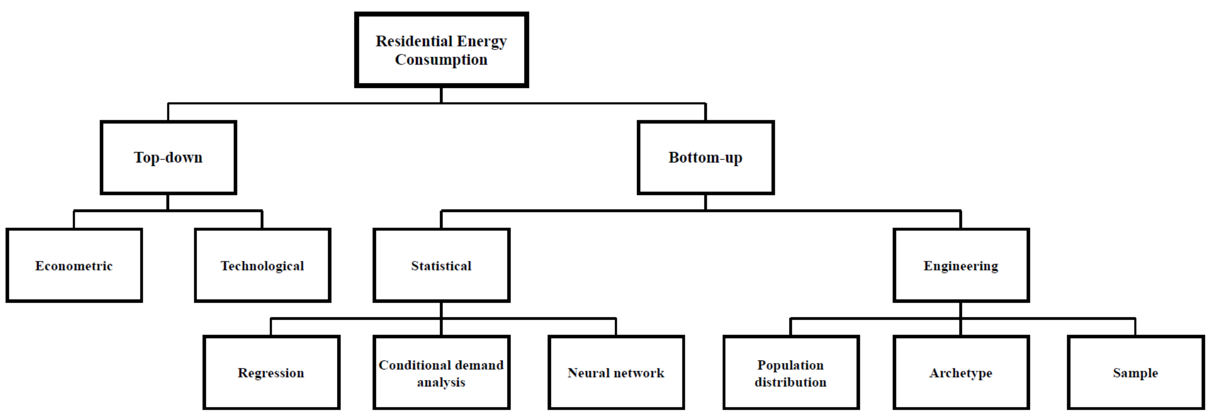


Figure 2.2. *Residential stock modelling techniques for estimating the regional or national energy consumption (own study, based on [251])*

The '*top-down*' approach assumes the residential sector as an energy sink, without investigating individual end-uses. The '*top-down*' models are based on widely available aggregated data and historic residential energy records. We might specify two types of the '*top-down'* approaches, depending on the used basis: econometric or technological. The use and development of the '*top-down'* approach started at the end of 1970s, after the energy crisis. The approach was used as a response to understand consumers behaviour after the crisis. Most of '*top-down'* models are based on statistical data and economic theory. According to [104], [105], [202], an annual housing energy models of the USA were obtained, based on econometric variables and status of the housing stock data. In [225], the similar model was presented for a residential stock model of New Zealand, with more technological focused – separate analysis of **s**pace **h**eating (SH) and **d**omestic **h**ot **w**ater (DHW). In 2001 a review of the simple economic model of Denmark's residential energy consumption was presented [38] – it was concluded, that long-term energy consumption is highly related with lagged energy consumption and its' pricing. Application of **g**enetic **a**lgorithms (GA) into Turkish residential stock modelling was proposed in [42], [204]. In 2005 the U.S. **D**epartment **o**f **E**nergy (DOE) [425] performed an econometric energy model of the USA housing stock – the **N**ational **E**nergy **M**odelling **S**ystem (NEMS). In [241], a Swiss model of the residential sector was defined in order to achieve energy consumption and greenhouse-gas emission targets – performed analysis was based on the effective reference area and census data.

The '*bottom-up'* approach includes all models which from a hierarchal level are lower than the whole sector as a unity. Models are defined with the energy consumption of individual houses or groups of houses and then extrapolated to the whole region. Usually, the input data for '*bottom-up'* models include parameters such as building geometry and envelope structure, equipment and appliances, exterior and interior climate conditions, occupancy and working schedules. The available '*bottom-up*' modelling methodologies referring to energy consumption within building stocks are reviewed in [131], [191], [260]. The biggest advantage of the '*bottom-up*' approach is a high level of details used during modelling process – it is possible to analyse the influence of advanced technological options on individual buildings as well as whole residential areas. There are two main classes of the '*bottom-up*' approach – statistical and engineering techniques. As it was shown in **Figure 2.2**, each technique can be further divided into 3 types of approaches. Commonly used techniques, following the statistical approach of the '*bottom-up*' method, used for modelling the housing stock, are listed below.

- Regression – technique uses regression analysis to reveal dependency between the model and input parameters. Usually, a combination of parameters, which are expected to affect energy consumption (*e.g.* weather data, enclosure thermal parameters or occupants behaviour) is investigated. Some exemplary analyses of regression method were presented in [106], [124], [214], [255].
- **C**onditional **D**emand **A**nalysis (**CDA**) – method uses a regression based on the occurrence of end-use appliances. The primary advantage of the CDA method is the availability of input data (mostly energy billing data). In order to obtain reliable results, the CDA method required data from hundreds or even thousands of houses. The CDA method was closely presented in [48], [149], [208].

- **N**eural **N**etwork (**NN**) – is a technique based on AI application by means of neural network (see more in section **2.8**). The NN technique uses a simplified mathematical model, with an interconnected structure similar to human brain structure. The NN technique is quite similar to the regression model. The application and development of NN methods in modelling energy consumption of residential stock have been historically limited, due to computational and data necessities. In [28] a literature review of the NN technique development used for electrical load forecasting of a buildings stock was presented. Residential stock analyses with the application of a NN technique were published in [29], [185], [270].

For the engineering approach of the '*bottom-up'* method, we might specify the following techniques.

- Distributions – a method which calculates the energy consumption of each end-use and aggregate on a regional or national scale in order to estimate the residential consumption. This technique does not account for interactions amongst end-uses. Some applications of distribution technique were published in [114], [125].
- Archetypes – a technique used to organize the analysed building stock according to house types and their size. The energy consumption of analysed archetype is scaled up to the size of the region. Typically, whenever a limited set of dwellings is representing a house type of the residential sector it might be called an archetype. Different archetypes are defined depending on the level of details within input data. In [206], the process of developing archetypes for energy simulations was presented – it was concluded, that there are 3 main criteria for defining archetypes: geometry parameters, thermal characteristics and operation data. Exemplary studies can be found in [45], [236], [237], [272], [294]. The archetypes technique is likely the most popular approach to building stock modelling.
- Sample – technique uses an actual exemplary house data as an input. Whenever the sample is representative for the analysed region, the large-scale estimations might be performed. While the archetype approach ensures limited housing stock, the sample method allows the high degree of variety. The method allows to include a wide variety of houses within the analysed stock. The sample technique is great to identify the energy consumption of residential regions. Due to a possible variety of houses, a large database is required. Some previous researches can be found in [73], [93], [152], [215] – in all cases, a huge number of sample houses data were used.

The '*pros & cons'* comparison of '*top-down'* and '*bottom-up'* (specifying statistical and engineering type) approaches is presented in **Table 2.1**. '*Top-down*' approaches required only limited data referring to prices, technologies development or climate conditions. The method is easy to develop; therefore, it is frequently used for building stock analyses. The '*top-down*' methods are based on historical data; therefore, they cannot be used to analyse a potential impact of novel technologies application. Those type of analyses is not helpful for policy and regulations implementations. There are two main types of '*bottom-up'* approaches – statistical and engineering. A detailed comparison of statistical and engineering approaches is published in [152]. The statistical techniques are capable to compromise national or regional economic changes with buildings' end-uses energy consumption. The engineering techniques are based on more detailed housing data – it is the simultaneous advantage and disadvantage of those techniques. Engineering models are capable to assume the occupant behaviour, which might highly affect buildings' energy consumption. The engineering approaches do not rely on historical data, nevertheless, those type of data might be used during the model calibration process. The '*bottom-up*' engineering technique is successfully used to evaluate the application of new technologies.

Usually, '*top-down*' approaches use historical data for long-term projections of energy demand analyses. '*Bottom-up'* statistical techniques determine the energy consumption of end-uses based on data obtained from information sources like energy bills or surveys. '*Bottom-up'* engineering techniques are used to calculate the energy consumption of end-uses based on a representative set of data, referring to the analysed housing stock.

Table 2.1. *Positive and negative attributes of the 3 major residential modelling approaches (source: [251])*

	'TOP-DOWN'	'BOTTOM-UP STATISTICAL'	'BOTTOM-UP ENGINEERING'
PROS	▪ INCLUSION OF THE ECONOMIC EFFECT ▪ SIMPLE INPUT INFORMATION ▪ ENCOMPASSES TRENDS	▪ ENCOMPASSES OCCUPANTS BEHAVIOUR ▪ INCLUSION OF THE ECONOMIC EFFECT ▪ USES BILLING DATA ▪ DETERMINATION OF END-USE ENERGY CONTRIBUTION	▪ MODEL NEW TECHNOLOGIES ▪ DETERMINATION OF END-USE ENERGY CONTRIBUTION ▪ END-USE BASED ON SIMULATION
CONS	▪ DEPENDENCE ON HISTORICAL DATA ▪ NO CLEAR INTERPRETATION OF END-USES ▪ SIMPLE ANALYSIS	▪ MULTI-COLLINEARITY ▪ DEPENDENCE ON HISTORICAL DATA ▪ RELIANCE ON A LARGE SURVEY SAMPLE	▪ ASSUMPTION OF OCCUPANT BEHAVIOUR ▪ DETAILED INFORMATION ▪ COMPUTATIONALLY INTENSIVE ▪ NO ECONOMIC FACTORS

Numerous studies related to residential energy consumption within building stocks were performed. The model proposed in [188] was aimed for a state of an electricity demand profile of a residential household.

The model was meant to output typical values of a residential demand profile – individual behaviour was modelled stochastically. The total electricity power demand was calculated as a sum of cold appliances, HVAC, lighting and activity-related power consumptions.

A study published in [175] introduced the ***E**nergy, **C**arbon and **C**ost **A**ssessment for **B**uilding **S**tocks* (ECCABS) model in accordance with a '*bottom-up*' approach. The performed analysis was based on a one-zone hourly heat balance (one-dimensional building energy balance) in order to obtain net energy demand for representative buildings of Sweden. The obtained results of representative buildings were extended to the entire buildings stock. As a result, the potential of a significant reduction in both, energy consumption and CO_2 emission, was presented for the Swedish residential sector.

In [26] a new method of presenting buildings stock results were proposed – using ***U**rban **E**nergy **M**aps* (UEM). At the urban scale, maps can provide useful information for estimating the profitability of retrofitting building stocks – it is a helpful approach for urban energy planning. Presented maps show an energy demand of buildings for space heating, by means of primary energy consumption per area (EP-factor) for a part of the Italian city – Benevento.

A novel calculation tool called *REMA* was introduced in 2014 [258]. The *REMA* is the tool developed in *MS Excel*, for assessing the effects of various energy-efficient measures for the whole building stock of Finland. The *REMA* tool uses an archetype approach from '*bottom-up*' methods of residential modelling. During the development of the *REMA* tool, previous studies of Finish residential sector were used.

Recently, a **G**eographical **I**nformation **S**ystem (GIS) is successfully used to estimate the energy consumption of residential stocks for city-scale areas. GIS was successfully used during the development of a statistical method, used during the analysis of energy consumption and possible savings for a building stock of Rotterdam city [174]. The major advantage of such methodology is a possibility of energy consumption prediction for a large scale building stock. Studies by means of the mentioned methodology can be performed relatively quickly and easy, without the necessity of large input dataset. GIS-based engineering models applied for city-scale approaches are frequently presented in the literature [44], [101], [253].

In [134] a physical simplifications and model order reduction approach [231] was implemented into residential stock analyses. It was concluded, that the simplifications did not affect the accuracy of energy consumption results significantly (errors within several % of annual energy outputs). Additionally, the final reduced building models accelerate the calculation time drastically, which is promising for urban analyses applications.

In [246] a comparison of twelve energy models was presented. Those models were examined in order to analyse accuracy, transferability and applicability to the energy demand results in the residential sector. The following models were checked: *LEAP* (**L**ong-range **E**nergy **A**lternatives **P**lanning) [293], *REM* (**R**egional **E**ngineering **M**odel) [244], *BSM* (bottom-up **B**uilding-**S**tock-**M**odel) [180], *MAED-2* (**M**odel for **A**nalysis of **E**nergy **D**emand) [296], *ECCABS* (**E**nergy, **C**arbon and **C**ost **A**ssessment of **B**uilding **S**tocks) [175], *CDEM* (**C**ommunity **D**omestic **E**nergy **M**odel) [78], *CREEM* (**C**anadian **R**esidential **E**nergy **E**nd-use **M**odel) [73], *BREHOMES* (**B**uilding **R**esearch **E**stablishment **H**ousing **M**odel for **E**nergy **S**tudies) [238], *REEPS* (**R**esidential **E**nd-use **E**nergy **P**lanning **S**ystem) [300], *DECM* (**D**omestic **E**nergy and **C**arbon **M**odel) [53] and *CHM* (**C**ambridge **H**ousing **M**odel) [287]. The presented study discusses both, advantages and disadvantages of the mentioned models applications into German residential stock case. From the analysis, a results compatibility stays in a range of 10-25 % (relative deviation error), depending on the model used. Out of the published research, it can be concluded, that each residential energy model is highly dependent on the input data. Moreover, from sensitivity analyses, it was proven, that the most influential parameters are those with are difficult to regulate by energy policies (*e.g.* occupants-related information or interior temperature). Also, specific conditions, such as exterior climate (especially if it is heating or cooling dominated), are extremely important during determining the most influential parameter. Finally, the necessity of further sensitivity analyses was established, each time, whenever a new building stock is analysed (different archetypes or countries).

In [52] a *CityBES* software [403] was presented. It is a new open web-based tool, supporting city-scale energy planning. The *CityBES* was developed by Lawrence Berkley National Laboratory [388]. The developed tool allows to define and simulate UBEM using the *Energy Plus* software (see more in section **2.7**) as the simulation engine and *Open Studio* as a development kit used to define simulation models for each building. *CityBES* software provides a city-scale energy modelling in accordance with '*bottom-up*', physics-based method. A procedure schema of the *CityBES* was shown in **Figure 2.3**. There are 3 main modules, related to data definition, simulation (algorithms) engine and use-cases. The performed study presents a *CityBES* tool application for a retrofit analysis of exemplary building stock (consisting of 940 buildings) located in northeast San Francisco. The software uses a detailed model of shading generated by the closest surroundings. As a final thought, the authors highlighted that further works are needed to establish, which features are most important in city energy analyses.

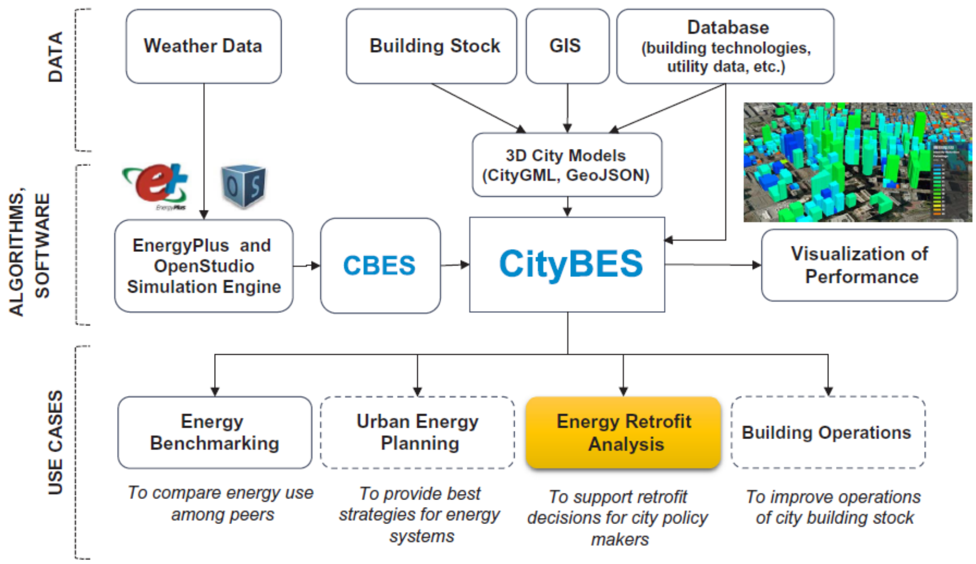


Figure 2.3. *CityBES software key components and data flow (source: [52])*

A review aimed at the overview of the relevant available simulation engines, which can be used for **U**rban-**S**cale **E**nergy **M**odelling (USEM) was presented in [245]. Short characteristics and possible applications of simulation engines into USEM approaches were made, considering the softwares like *DOE-2* [374], *ESP-r* [380], *Energy Plus* [378] or *TRNSYS* [424]. USEM and UBEM are related to the same area of application – both phrases can be used interchangeably.

One of the most interesting and promising work within UBEM field was published in 2018 [95]. The performed study was focused on the presentation of a computational platform which is capable to integrate renewable energy technologies and building renovation simultaneously (developed to conduct comprehensive urban analyses). The performed case-study is focused on a Swiss village (with a population of approx. 900 citizens), consisting of 150 buildings with different functionality, distributed primarily along the main streets. A developed platform consists of several existing tools, accordingly *QGIS* [421] (open-source geographical information system), *Rhinoceros 5* [422] (used to prepare 3D geometrics of the buildings), *CitySim* [404] (used to simulate the energy consumption via building stock), *HOMER Pro* [386] (micro-power optimization model, developed by U.S. National Renewable Energy Laboratory [416]), and *Ms Excel*. The procedure of the performed study can be seen in **Figure 2.4**. Within the work, improvements in electricity, as well as heat generation, were explored. The obtained results showed, that heating demand can be reduced up to 85 % and more importantly, a reduction in fluctuations in energy demand was observed. Also, it was proven, that a RES application is highly promising – contribution of PV systems with wind turbines can cover up to 60 % of the total energy demand. The necessity of hybrid energy systems (*e.g.* solar and wind) was highlighted – each energy source complements the other one.

Additionally, a basic analysis of an application of energy storages was performed in order to overcompensate the mismatch in the peak energy production and demand. Unfortunately, it turned out that energy storages are economically unprofitable at present.

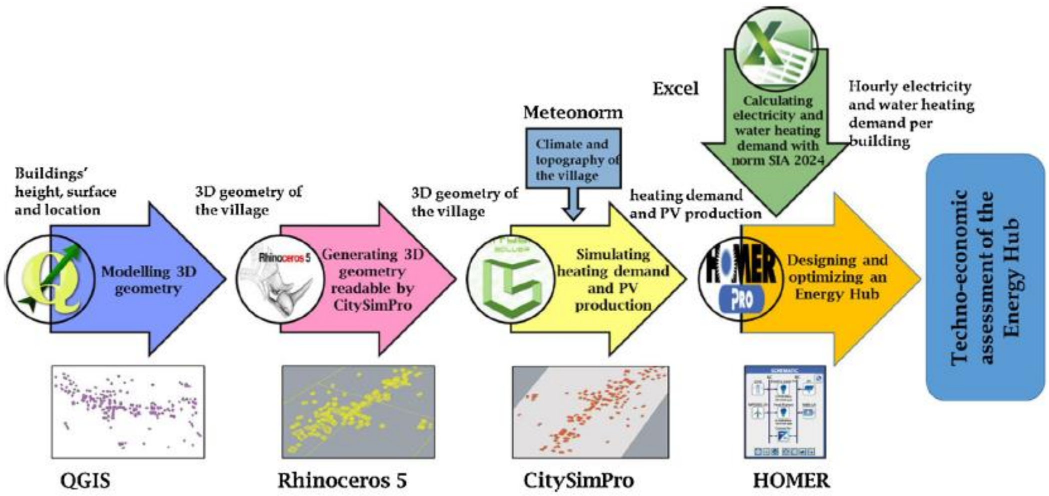


Figure 2.4. *Schema of a computational platform developed for UBEM analyses (source: [95])*

The researches [95] were continued and resulted in the second article published one year later, in 2019 [186]. The performed analysis was extended by adding development scenarios (predictions) for Swiss village for the years 2030 and 2050. The performed study includes consideration of future energy demand and energy generation, simultaneously with uncertainties related to technological improvements and prices records. Procedure schema shown in **Figure 2.4** remains the same, only with different goals; this time the aim is focused on future urban form and energy system assessment. Results were presented using maps, representing heating and cooling demand of the analysed region. Two main recommendations related to the future urban form as well as energy system design and optimization were set. The results showed, that due to global warming a cooling demand will increase by up to 115 % in 2050. Once again, a great potential of RES integration into the grid was proven – a hybrid system consisting of wind turbines and PV systems can supply up to 77 % of a 2050 annual demand.

In [275] a review of urban modelling was combined with RES application into building cluster. According to [261], [275] a building cluster can be defined as '*a group of buildings systematically interconnected to the same energy infrastructure so that a change of energy performance of a single building affects both the energy infrastructure and other buildings of the cluster either in a synergic or a disruptive way*'. Building cluster issue is also one of major topics within ongoing research project *Annex 67-Energy Flexible Buildings* [123] of the **E**nergy in **B**uildings and **C**ommunities (EBC) [406] of the **I**nternational **E**nergy **A**gency (IEA) [413]. The building cluster approach is a method which is highly promising to maximize the synergies of

RES usage with highly-efficient urban energy management. It was probably the first time when the *Energy Cluster* concept (see more in section **2.6**) was applied into UBEMs. Authors were motivated by answering a question: '*How energy is matched in the cluster with RES envelope solutions*?'. The review of the building cluster modelling procedure was summarized in **Figure 2.5**. It was concluded, that energy planning at building cluster level is potentially a breakthrough in the wide-spread implementation of RES into urban areas.

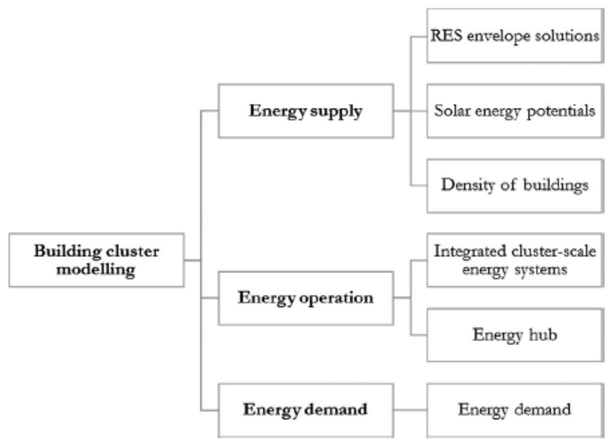


Figure 2.5. *Schematic logic (procedure) of the building cluster modelling (source: [275])*

In [261] the concept of the novel, innovative approach of UBEMs was introduced – **E**nergy **F**lexible **B**uilding **C**luster (EFBC). The concept of **E**nergy **F**lexible **B**uilding (EFB) is defined as a building able to manage its demand in various exterior conditions. Regarding the cluster level, it is extremely promising to investigate building cluster consisting of EFB – the EFBC approach allows to model load and demand of a local grid. In the article, authors present the overview of the theory and existing guidelines to evaluate the EFBCs. The work initiated a movement of researches and overviews for policymakers in order to deal with the new topic of the EFBC concept.

High interest in researches within UEM field continues – even in early 2020, some articles have been already published. In [165] a novel **L**ocal-**W**eather **D**istributed **A**djacency **B**locks (LW-DAB) model was introduced. The LW-DAB model combines '*bottom-up'* simulations and customized local micro-climate clusters. The defined model considers the impact of the **U**rban **H**eat **I**sland (UHI), dependent on factors like buildings density and height, as well as sky view factor, solar reflectivity, heat capacity and land surfaces roughness [200]. Due to the growing impact of cites in overall energy consumption distribution, the UHI studies are a popular topic of researches [49], [111], [139], [140], [249]. The analysis was performed for a city digital model, consisting of 1175 buildings (some results are presented in **Figure 2.6**). The proposed LW-DAB model abbreviates the simulation time by half, with only 5% accuracy loss compared with the standard city-scale simulations. The presented studies incorporate both, inter-building effects and local climate conditions. It was concluded, that the LW-DAB model is capable to perform computational simulations of city-scale regions with satisfying accuracy. The LW-DAB model can be successfully used for urban planning.

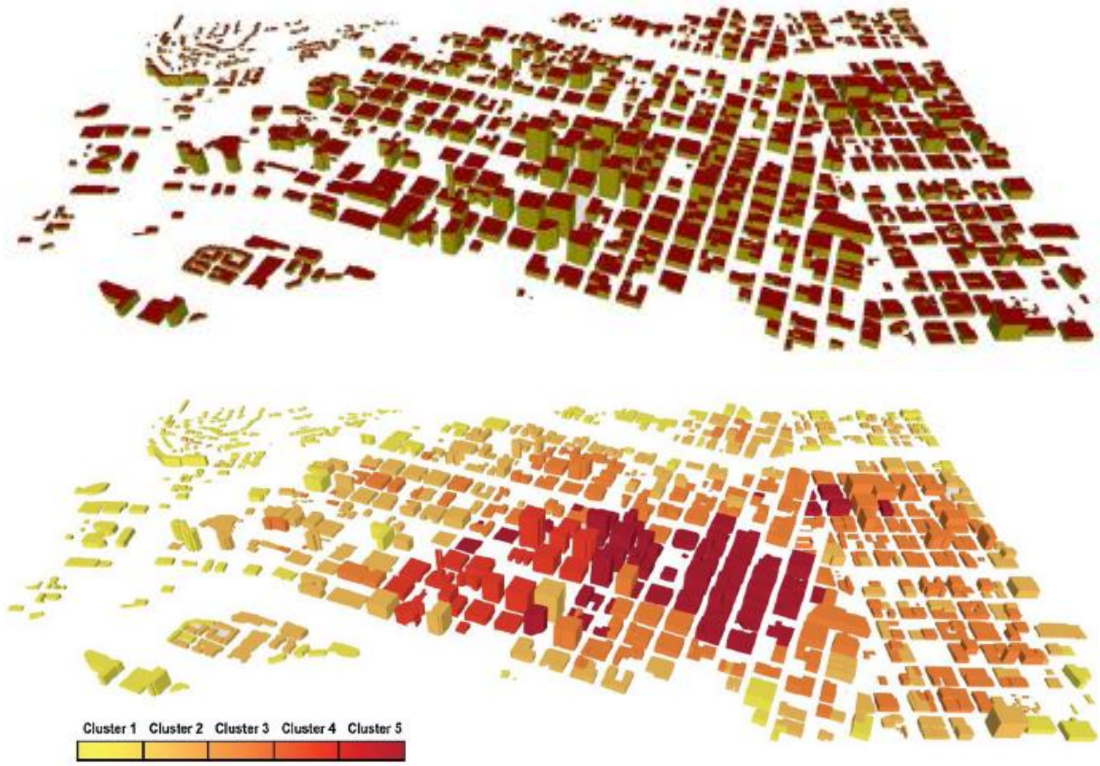


Figure 2.6. *The 3D city building energy model (up) and clustered UHI intensity results (bottom) (source: [165])*

CONCLUDING REMARKS

Recently, buildings energy efficiency becomes a crucial aspect to develop sustainable cities. City-scale analyses are characterized by huge complexity – existing simulation tools for **U**rban **E**nergy **M**odeling (UEM) require significant computational resources. Development of novel tools for UEM analyses became a popular trend for engineers, researchers and scientist all over the world. Those tools should preserve a complex methodology of heat and mass transfer in buildings, include the impact of exterior climate and urban-shape, as well as abbreviate calculation time holding up the satisfying accuracy of obtained results. Fulfilment of these principles set is doubtlessly a difficult and ambitious task. After all, urban modelling is a nascent field which should engage and support city-scale energy modelling in the nearest future –it is extremely important for urban sustainable development.

The UEM analyses can be considered as building cluster studies. It is crucial to fully understand thermal processes in building elements whenever a large area consisting of numerous buildings is examined. Only then, an accurate model of a city-scale building cluster can be correctly defined. Knowing the energy performance of buildings, it remains to define (with appropriate complexity) interactions related to buildings surrounding and the environment. Nevertheless, reliable UEM predictions related to city-scale building clusters remains an open topic of research. Unfortunately, only limited studies about urban morphology impact on city-scale energy demand have been performed. Those type of studies is extremely important for the sustainable development of cities and global environmental protection. Therefore, the energy-related analyses at an urban scale attract numerous studies in recent years.

2.2. OVERVIEW OF THE ELECTRICAL ENERGY SYSTEM OF POLAND

Whenever we consider an energy supply, it is obvious that heat or electricity is taken into account. Energy might be produced within the national electricity grid or locally, by individual consumers or local heat suppliers (*e.g.* district heating networks). To guarantee a stable national grid, as well as for appropriate building management, both ways of energy production are necessary. Additionally, local energy production out of renewables usage is a key factor of highly energy-efficient buildings.

National electricity production of Poland is based on conventional fuels, mainly coal [316], [397]. The most important concern is whether Poland will end its toxic relationship with coal. A detailed mix of fuels used in Poland during electricity production is presented in **Figure 2.7** and **Figure 2.8**. It can be clearly seen, that since the start of the XXI century, the Polish energy system is based on coal and other conventional fuels. Moreover, the Polish structure of electricity production remains almost unchanged, despite the growing development and usage of renewable sources. Sadly, in 2015, 83.2 % of produced electricity in Poland comes from environmental-unfriendly coal (accordingly 46.1 % from hard coal and 37.1 % from brown coal). Unfortunately, in 2015, green energy constituted only 13.1 % of national production, with a total annual amount of produced electricity equal to 20.6 TWh/a.

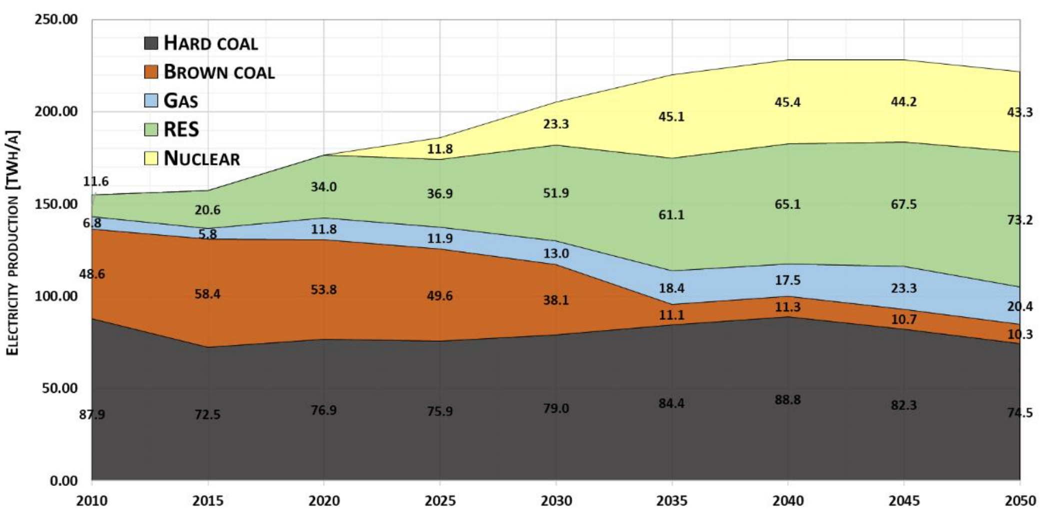


Figure 2.7. *Electricity production mix of Poland - 2050 forecast (own study, based on: [301], [377], [397])*

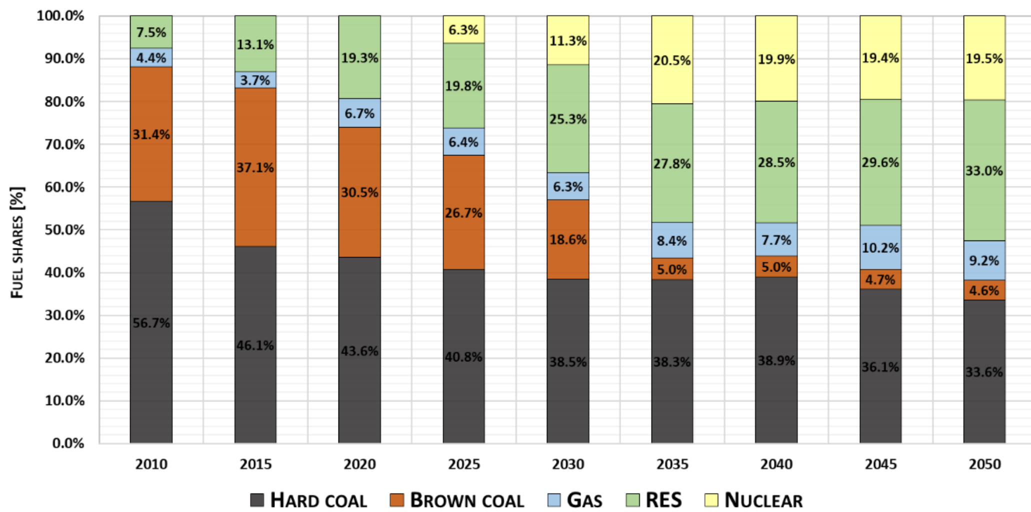


Figure 2.8. *Fuel share in Polish electricity production – 2050 forecast (own study, based on [301], [377], [397])*

In **Figure 2.9** we can observe a share of renewables used in Poland in 2018. According to [316], in 2018 a wind energy was the main source of green energy, with total electricity output of 12.8 TWh/a (approx. 59 % out of all environmentally-friendly sources). It is an unaccepted fact, that presently we observe a suppression of wind energy development in Poland, due to regulations referring to the placement of wind turbines [343] (onshore wind energy development of Poland almost stopped since mid-2016). Surprisingly, solar energy stands only for 0.3 TWh/a (approx. 1 %) within national electricity production, despite that kind of renewable source is the fastest growing and developing all over the world [320]. A rapid increase in renewables usage for electricity production can be observed in many countries. Poland was also on the right track till 2015, when the amount of electricity produced out of renewables was stabilized and remains at a similar level till today. The Polish government should encourage potential investments within green energy solutions.

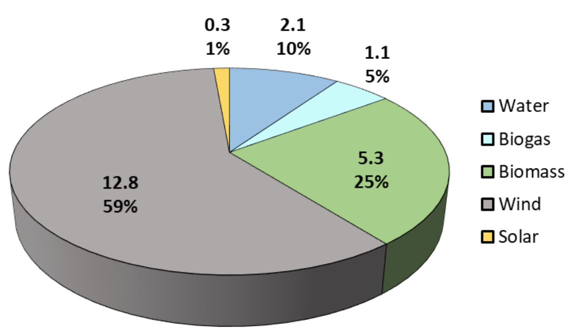


Figure 2.9. *Share of Renewables in electricity production of Poland in 2018 (own study, based on: [316])*

Most of the electric energy in Poland is produced by 5 main **D**istribution **G**rid **O**perators (DGO). Each of them has its own strategies and plans for future development. Moreover, those enterprises constantly compete for consumers with many different offers of energy supplies. In **Figure 2.10** we can observe the territory divided among the energy suppliers in Poland.

Figure 2.10. *Territorial influence of main energy operators of Poland (source: [370])*

For the Polish climate it is typical to observe both cold winters and hot summers – even today, with the undeniable impact of global warming, the winter period occurs in Poland each year. The national grid needs to ensure energy supply during peak demands, which in Poland can be easily distinguished as winter and summer peaks. Typically, the winter peak is much higher in Poland compared with the summer one, but in the nearest future, both demands will aim to level out [304], [397].

According to the actual trends of environmental protection due to global warming, the necessity of renewables usage is unquestionable. As it was mentioned before, Polish electricity production is based on conventional fuels, which are highly environmentally harmful. A transformation of the Polish energy system, unfortunately, seems to be much slower compared with the global trend – comparing with other EU countries, we are observing a slow redevelopment of Poland's energy system by means of renewables application. Without a new strategy for the Polish national electro-energetic system, it will become impossible to reach the EU’s targets regarding the share of renewables in national energy consumption for the years 2020 [331], [332], [333], [334], or 2050 [307], [308], [309], [310].

Also, a present fuel policy of the Polish energy system seems to be incompatible with a world-wide policy against global warming, based on lowering greenhouse gas emissions (especially CO_2).

2.3. POLISH RESIDENTIAL BUILDING STOCK

Poland has 37.8 mln registered residents at the end of 2019. A slow decrease in population is observed since 1999 when it reached a peak value of 38.66 mln citizens (year-by-year drop by approx. 0.15 %). The median age of Polish is constantly rising – at the end of 2019, statistical resident of Poland was 41.9 years old, with predicted lifespan around 78 years, 51.6 % of citizens are women, while 48.4 % are men. The population density of Poland is stable over the past years at the level approx. 124 people/km^2. The population in each province of Poland was presented in **Figure 2 11**. In 2019 over 60 % of citizens (approx. 22.92 mln) were living in cities while the rest of them (approx. 14.88 mln) choose the countryside. All provided data related to Polish demography is based on [317], [419], [420].

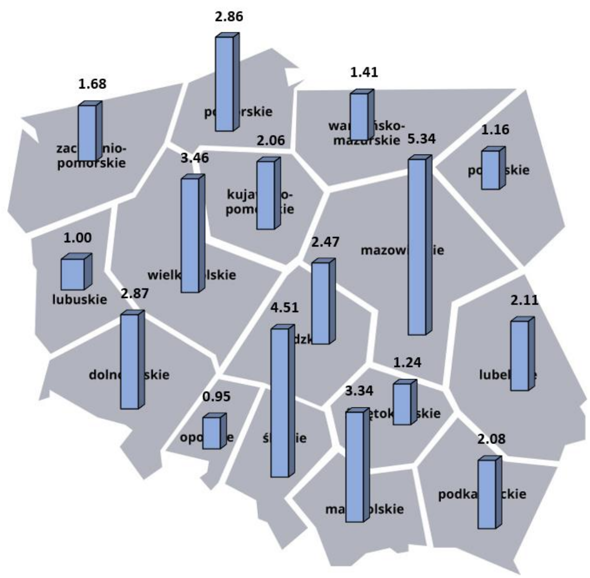


Figure 2 11. *Polish demographic data on population (mln) in each province of Poland (own study, based on:[317])*

Residential buildings can be divided into 2 main groups: single-family and multi-family buildings. According to [318], [319] a collation of Polish residential building resources is presented in **Table 2.2**. The presented data has not included information related to the newest buildings, constructed after 2010 (modern buildings are characterized with much better thermal properties compared with the older ones). Single-family houses are a majority of residential buildings in Poland, constituting approx. 90.98 % of all dwellings. An interesting fact is that despite the overwhelming amount of single-family houses compared with multi-family houses, only approx. 39 % of Polish are living in their own houses. It can be clearly seen, that most of the residential buildings of Poland were constructed in the previous century: approx. 89.44 % of single-family houses and 89.94 % of multi-family houses. It causes a high energy demand of the residential sector, which might be significantly limited due to the implementation of the strategies providing an energy efficiency improvement. Typically, those strategies are limited to building thermal refurbishment and modernization of heating systems, but nowadays it is crucial to apply advanced techniques of highly energy-efficient buildings into the residential sector (see more in section **2.4**).

Table 2.2. *Polish residential buildings stock (source: [317])*

BUILT PERIOD	SINGLE-FAMILY HOUSES		MULTI-FAMILY HOUSES	
	AMOUNT [-]	SHARE [%]	AMOUNT [-]	SHARE [%]
before 1945	1 002 119	21.55	219 303	46.66
1946-1970	1 279 382	26.98	85 160	18.12
1971-2002	1 940 032	40.91	118 275	25.16
2002-2010	500 756	10.56	47 301	10.06
TOTAL	4 742 289	-	470 039	-

According to data published in [315], the thermal-modernisation statistics within the residential sector are presented in **Table 2.3**. Unfortunately, residential buildings in Poland are characterized by poor thermal properties resulting in high energy consumption (detailed description of average single-family houses of Poland is presented in subsection **2.3.2**). The necessity of buildings refurbishment is undeniable – the average single-family house in Poland consumes more than twice energy compared with German ones [412] (accordingly 130 kWh/m^{2}a and 53 kWh/m^{2}a). Being more precise, according to the scientific report published in 2017 [312], the statistical energy performance of single-family houses in Poland was obtained. Buildings were divided into 5 groups, depending on their energy performance, starting from a very low standard (uninsulated buildings), ending with a very high level (enclosure with thick insulation layer). Sadly, in 2017, 88.4 % of single-family houses in Poland have an unsatisfying energy performance level, while only approx. 1 % are marked as highly-energy efficient buildings (**Figure 2.12**). Within the report [312] the estimation of total expected costs of investment in Poland, in order to obtain high energy standard for all single-family buildings, was performed. The considered investments are related to insulation of exterior walls, roof renovation (including thermal insulation), replacement of windows and exterior doors, heating system modernisation as well as kitchen and bathroom renovation (water conservation and lower bills). The total amount of approx. 78 bln PLN has to be invested in order to assure a high energy efficiency level of the national single-family building sector.

Table 2.3. *Thermo-modernisation statistics of the residential sector in Poland (source: [315])*

BUILT PERIOD	% OF THERMO-MODERNISED BUILDINGS
before 1945	7
1946-1966	11
1967-1985	16
1986-1992	14
1993-2002	8
2003-2008	N/D *
after 2008	N/D *

Where: * it was assumed, that these are new buildings fulfilled as obligatory energy-efficient standards

Figure 2.12. *Energy performance of single-family houses in Poland (source: [312])*

2.3.1. EPISCOPE AND TABULA PROJECTS

The building refurbishment process is a key solution towards a highly energy-efficient household sector. In 2013, the European project entitled *EPISCOPE* (**E**nergy **P**erformance **I**ndicator Tracking **S**chemes for the **C**ontinuous **O**ptimisation of Refurbishment **P**rocesses in **E**uropean Housing Stocks) has been launched, as a follow-up the *TABULA* (**T**ypology **A**pproach for **Buil**ding Stock Energy **A**ssessment) project [379]. Both projects were funded by the **I**ntelligent **E**nergy **E**urope (IEE) programme, which was a part of the European Union support budget for research within energy-efficient technologies (presently substitute by the EU's Horizon 2020 programme). The long-term goal of both projects was to help to reach the climate protection target by actions and strategies applied within the building sector.

The *TABULA* project started in 2009 and finished in 2012. In a nutshell, the major assumption of a project was to develop residential buildings typologies in 13 European countries (see **Figure 2.13**). Each national typology is based on a classification of buildings according to their size, age and further parameters. Also, for each group, an exemplary representative building was defined. In the end, the developed-national building typologies were published by the project partners in the *Building Typology Brochures*. In the brochures, *Building Display Sheets* are presented graphically, for all the representative buildings including energy-related features and the effects of refurbishments. Each brochure is written both in English and the language of the country. Additionally, the project includes a *TABULA WebTool* – an online calculator of the exemplary buildings from all the countries [399]. The primary objective of the *TABULA WebTool* is the formula for calculation of the building energy profile (primary energy, CO_2 emission, costs).

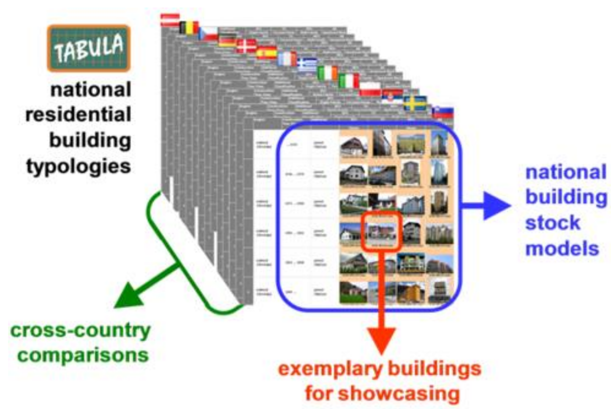


Figure 2.13. *Schema of the TABULA project assumptions (source: [379])*

The National Energy Conservation Agency (in Polish: ***N**arodowa **A**gencja **P**oszanowania **E**nergii,* NAPE) [393] elaborated the Polish Building Typology [315]. The main purpose of the developed typology was to present a general overview of the Polish buildings' energy performance. Moreover, those kinds of analyses are helpful for building managers, housing associations and housing owners to decide on building modernization. According to *TABULA* project guidelines, Polish building typology includes:

- a classification of the residential building stock (the building type matrix);
- frequency of the building types;
- set of exemplary buildings for each group of the national stocks;
- typical energy profiles of the exemplary buildings;
- possible energy savings (refurbishment measures);
- statistical data referring to buildings and supply systems.

In the Polish building typology, NAPE has defined two types of buildings, which can represent the set of each group:

- **average building** – virtual building, composed of the most typical elements for defined building types; used to validate the application of the modernization for existing buildings;
- **example building** – a real building, representative for a defined group; used for energy-saving potential analyses.

For each of the main group, an average building has been defined. The national typology was developed due to the agreement with the *Build Desk* company [368]. The total amount of 60 thousand building certificates registered in the *Build Desk* company database and over 2 thousand from the NAPE database were used. All the considered buildings have not been the subject of thermal-renovation. The Polish building stock was divided into 4 groups (the same as adopted by the *TABULA* association), with 7 construction periods (see **Figure 2.14**):

- **s**ingle-**f**amily (SF) – buildings with 1 apartment;
- **t**erraced **h**ouse (TH) – buildings with 2-4 apartments;
- **m**ulti-**f**amily **h**ouse (MFH) – buildings with more than 4 apartments, up to 8 floors;
- **a**partment **b**locks (AB) – buildings higher than 8 floors.

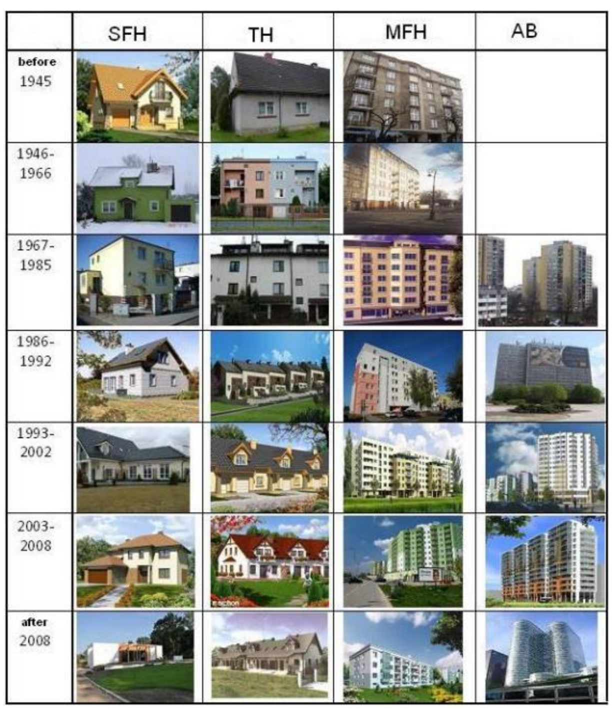


Figure 2.14. *Polish building matrix according to TABULA report (source: [315])*

The building typologies have proved to be a useful instrument for an in-depth understanding of the energy performance of certain building types and categories. Great potential for energy efficiency and reduction of energy consumption was provided in the *TABULA* report.

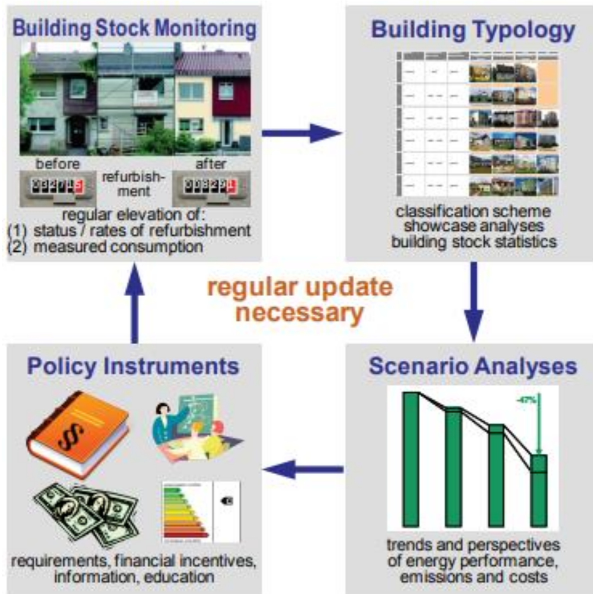


Figure 2.15. *EPISCOPE project procedure schema (source: [313])*

Various instruments and policies have been applied to the building sector in order to improve energy efficiency, however, there is poor evidence for the overall success of these actions. The main goal of the *EPISCOPE* project was to make a building sector refurbishment process more transparent and effective [313], [379]. As it was already mentioned, a conceptual framework was based on the already defined national residential building typologies, developed during the *TABULA* project. The main objective was to track the energy savings of the housing stocks on a local, regional or national level. Also, different refurbishment variants were checked in order to attain the crucial climate protection targets. The *EPISCOPE* project is also a great guidebook that provides useful information about the new buildings' design process acquiescent with **N**early **Z**ero **E**nergy **B**uildings (NZEB) standard (see more in section **2.4**). Unfortunately, Poland has not participated in the *EPISCOPE* project. The major outputs and expected results of the *EPISCOPE* project (procedure presented in **Figure 2.15**) are:

- an extension of the national residential building typologies developed during the *TABULA* project to further countries;
- pilot various of actions resulting in improvement of buildings energy efficiency, especially thermal refurbishments or renewables application;

- evaluation of scenarios for the analysed housing stocks, in particular, energy savings and CO_2 reductions or achieving NZEB standard;
- recommendations on how to monitor residential sector energy efficiency improvement.

The main outcome is to ensure a highly energy-efficient building sector. It might be possible only if high-quality refurbishments are performed, according to transparent national regulations and the renovation process and potential energy savings are monitored. A long-term objective is to obtain procedures for each European country related to energy certification and energy management. The additional result obtained during the *EPISCOPE* project was a map of Dublin, with buildings distribution by construction periods (see **Figure 2.16**). Those kinds of results are extremely important for local energy-related analyses of residential areas. The Irish case study – related to the North-side of Dublin city, presents monitoring energy refurbishment levels of housing stock using a mapping approach. The mapping method can successfully assist in retrofit strategy development and planning of residential areas. An interesting fact is that results from the *EPISCOPE* project were published in a special issue of the '*Energy and Buildings'* journal, with a heading issue entitled: '*Towards an energy-efficient European housing stock: monitoring, mapping and modelling retrofitting processes'*. Published articles refer to dynamic building modelling [226], [229], building stock characteristics and energy performance of residential buildings [60], [68] or refurbishments scenarios profitability [57], [65]. The final results of the *EPISCOPE* project were published in [295].

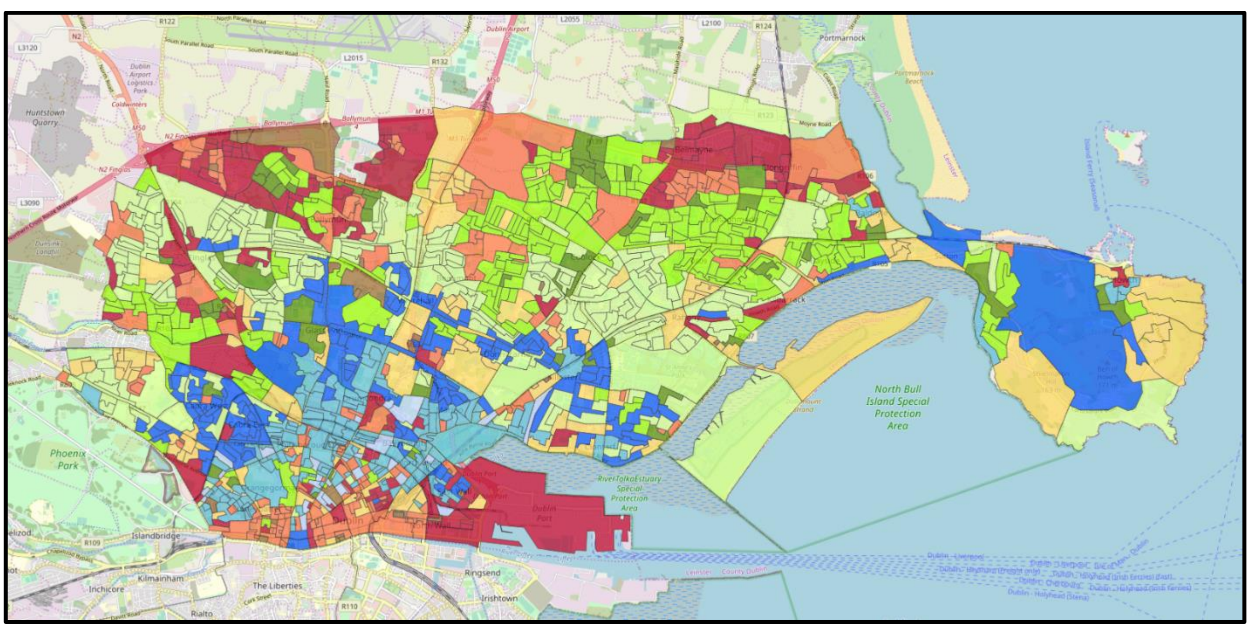


Figure 2.16. *Map of Dublin with a layer of buildings distribution by construction periods, obtained during EPISCOPE project (source: [405])*

2.3.2. REFERENCE POLISH SINGLE-FAMILY HOUSES

This section is focused on the presentation of the reference single-family houses in Poland, according to [315]. Single-family houses are the most popular and most numerous building types in the Polish household sector. In what follows a short description of each single-family building group was presented with a collation of major building parameters shown in **Table 2.4**. Additionally, all building parameters, used during the *TABULA* project are collated in **Appendix 1**.

Table 2.4. *Characteristics of Polish representative single-family houses (source: [315], [379])*

	RSFH_1	RSFH_2	RSFH_3	RSFH_4	RSFH_5	RSFH_6	RSFH_7
A_{TOT} [m^2]	84.00	115.00	154.00	160.00	180.00	203.00	220.00
A_o [m^2]	72.00	98.20	128.60	140.30	160.10	175.50	188.20
V_o [m^3]	180.50	245.50	330.80	408.00	448.30	501.20	540.00
A/V [1/h]	1.19	1.16	1.06	0.96	0.97	0.95	0.94
U_{WALL} [W/m^{2}K]	1.70	1.70	1.18	1.40	0.50	0.28	0.29
U_{ROOF} [W/m^{2}K]	0.85	0.75	0.65	0.50	0.50	0.40	0.35
U_{FLOOR} [W/m^{2}K]	2.35	1.95	1.75	1.50	1.10	0.70	0.60
$U_{WINDOWS}$ [W/m^{2}K]	5.15	5.15	2.75	2.70	1.70	1.30	1.20
U_{DOORS} [W/m^{2}K]	5.10	4.50	4.00	3.60	2.50	1.80	1.70
HEATING SYSTEM COP	0.59	0.59	0.59	0.86	0.87	0.87	0.87
HEATING SYSTEM FUEL	C	C	C	G	G	G	G
DHW COP	0.59	0.59	0.59	0.59	0.70	0.70	0.70
DHW FUEL	E	E	E	E	G	G	G
VENTILATION SYSTEM	N	N	N	N	N	N	N
EK [kWh/m^{2}a]	348.00	327.00	253.00	186.00	160.00	140.00	141.00

Where: A_{TOT} – total building area, A_o – heated area, V_o – volume, **A/V** – shape factor, U_{WALL} – thermal transmittance of exterior walls, U_{ROOF} – thermal transmittance of a roof, U_{FLOOR} – thermal transmittance of the ground floor, $U_{WINDOWS}$ – thermal transmittance of windows, U_{DOORS} – thermal transmittance of exterior doors, **EK** – end-use energy factor; C – coal; G – gas; E – electricity, N – natural ventilation

According to the *TABULA* report, 7 types of average buildings were defined for the Polish single-family sector (see **Figure 2.17**). Above mentioned buildings will be furtherly named as **r**epresentative **s**ingle-**f**amily **h**ouses (RSFH). They were characterized with different construction periods, and their various building parameters are given. The oldest group of buildings were defined as ones built before 1945, while the newest were constructed after 2009. The following types of reference single-family houses of Poland are defined:

- constructed before 1945 (RSFH_1);
- constructed between 1946-1966 (RSFH_2);
- constructed between 1967-1985 (RSFH_3);
- constructed between 1986-1992 (RSFH_4);
- constructed between 1993-2002 (RSFH_5);
- constructed between 2003-2008 (RSFH_6);
- constructed after 2009 (RSFH_7).

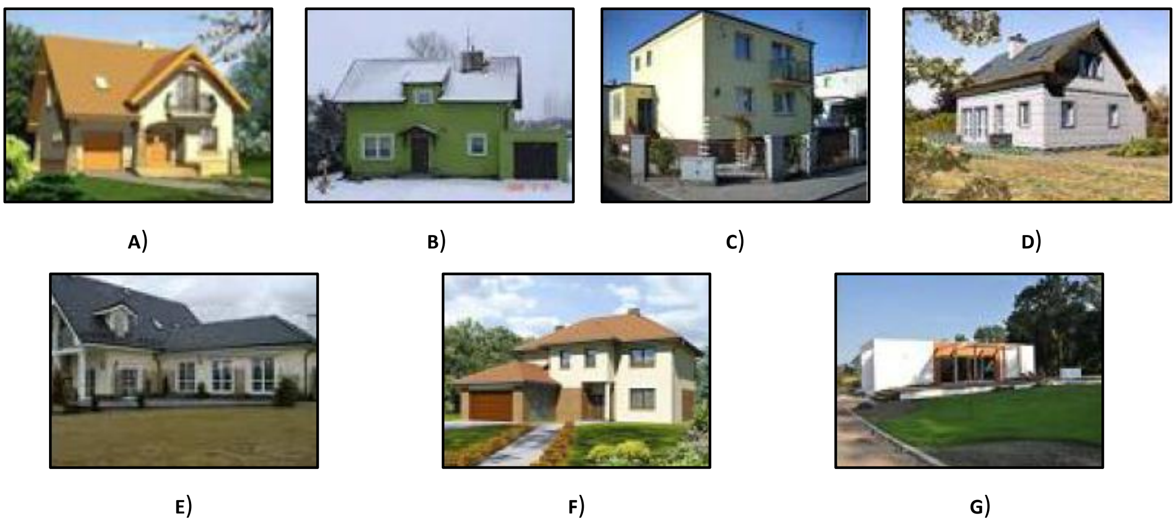


Figure 2.17. *Pictures of representative single-family houses of Poland, accordingly: A) RSFH_1; B) RSFH_2; C) RSFH_3; D) RSFH_4; E) RSFH_5; F) RSFH_6; G) RSFH_7 (source: [315])*

Looking at the presented statistical data, it can be clearly seen, that the selection of building types was based not only on the construction period but also their energy characteristics. It can be clearly seen from the statistical data, that nowadays larger houses with more windows are constructed, comparing to the past. Transformation of a building's geometry has a significant impact on their energy characteristics – modern single-family houses of Poland have a more compact design (decreasing buildings' shape factor). Having a closer look at the energy characteristics of each building type the following conclusions were noted.

- RSFH_1 and RSFH_2 types are the least energy-efficient buildings –the high need for their thermal-renovation. Building facilities have a low **c**oefficient **o**f **p**erformance (COP) and their envelope is uninsulated. Additionally, environmental-harmful coal is used for heating purposes. Moreover, the

EK factor value is unacceptable – almost 4 times higher compared with the actual Polish regulations [346].

- For RSFH_3 type a clear decrease in energy demand was observed, expressed by means of the EK-factor value. The lower value of an EK-factor compared with the previous building types is caused by higher thermal parameters of a building enclosure (*i.e.* lower values of thermal transmittance). Nevertheless, the third group of representative single-family houses of Poland is still far from the standard of energy-efficient and environmental-friendly buildings.
- RFSH_4 and RSFH_5 are characterized by a slight improvement in overall thermal parameters of building enclosure comparing with RSFH_3. The COP improvement of a heating system (for RSFH_5 also for a DHW system) should be highlighted. Also, coal was replaced with natural gas, which is much more environmental-friendly fuel.
- RSFH_6 and RSFH_7 are very similar to each other. They have a well-insulated building enclosure with highly efficient facilities. The EK-factor value is close to the national regulations, according to [346]. Only those two types of single-family buildings do not obligatorily need a thermal-renovation. However, they are still a huge potential for energy efficiency improvement for those types of buildings (*e.g.* reaching nearly zero energy building standard).

2.4. HOW TO IMPROVE BUILDINGS' ENERGY EFFICIENCY?

Due to a high share in primary energy consumption by buildings in cities, improving buildings' energy efficiency is a key strategy towards sustainable urbanization. In this chapter, a brief and up-to-date overview of methods resulting in improvement of buildings' energy efficiency is made. The most important and popular techniques and strategies are listed and discussed. After all, the development of highly energy-efficient buildings is a fundamental aspect of the residential sector of the future.

In general, all operations which result in lowering energy demand are defined as energy efficiency techniques (see **Figure 2.18**). The energy efficiency concept can be expressed based on the three pillars, accordingly direct modernizations (energy savings), energy solidarity (based on local norms and regulations) as well as social aspects, widely called energy sobriety [12]. Nevertheless, those operations do not affect the typical use or purposes of the subject, on which the above-mentioned techniques are applied. According to [193], at the EU-level, the major potential of energy efficiency improvement is in the single-family and multi-family houses (residential sector). For that reason, the subject will be understood as a building (or more generally as a whole residential sector), while the operations are considered as improvements, resulting in improvement of buildings' energy efficiency. The idea of energy efficiency improvement might be considered in numerous ways, but it is always estimated by comparison of a building state before and after performed modification.

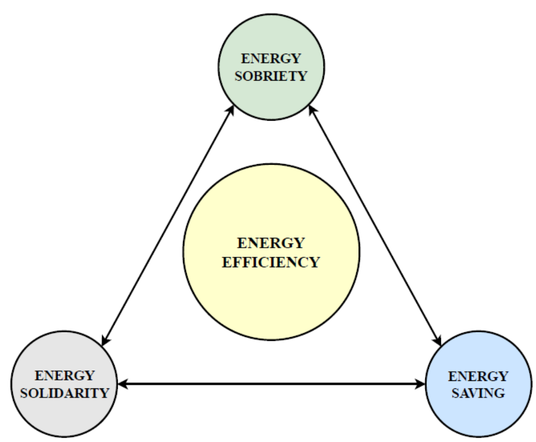


Figure 2.18. *Simple energy efficiency schema (own study)*

The residential energy demand profile depends on multiple factors, including the climate conditions, dwelling characteristics but also the household members activities. The major end-use groups of energy consumption in buildings are **S**pace **H**eating (SH), **S**pace **C**ooling (SC), **D**omestic **H**ot **W**ater (DHW) and **A**ppliances & **L**ighting (AL). There is a long list of the modernizations applied for buildings, resulting in an improvement of their energy efficiency. The main fields of building energy efficiency improvements are focused on proper building design [47], [67], [89], [179], [203], [213], its refurbishments [23], [37], [43], [115], [170], [328], fenestration replacement [64], [94], [96], [121], [166], [222], [262], optimization and management of building facilities [151], [233] or usage of renewable energy sources [51], [107], [221], [274].

Building modernizations might be a quite simple project based on just an improvement of thermal parameters of the enclosure, or a comprehensive approach which includes more advanced strategies. Whenever a building refurbishment is considered, the following technical aspects are recommended to be analysed [115]:

- **I**ndoor **E**nvironment **Q**uality (IEQ) – a key issue for health and welfare of the occupants, considering aspects of *i.a.* humidity, thermal comfort or air quality,
- energy use – a potential energy reduction by SH, DHW, SC or AL systems,
- local resources and regulations overview to select some appropriate solutions,
- costs – including the whole refurbishment process: management of the work, labour and material prices,
- retrofit measures – compilation and analyses of potential savings.

It is crucial to perform a thermo-renovation in the proper order of executed modernizations – otherwise, there is a risk of losses in obtained profits (both, in terms of energy efficiency, as well as financial aspects). In the end, we should always peruse for an energy-efficient building as possible. The schema on how to perform building's modernization to improve its' energy efficiency is presented in **Figure 2.19**. Firstly, we should always perform an energy analysis of the building, in order to estimate its energy consumption (stage **A**). This assessment allows us to plan an appropriate assortment of modernizations for the analysed situation. The first set of building improvements should always refer to its' enclosure (stage **B**) – highly energy-efficient buildings required well-insulated envelopes. Whenever the analysed building has a well-insulated enclosure, the required facilities might be selected, to ensure appropriate indoor climate conditions. Replacement of the worn-out systems for the modern and efficient ones is a next step towards building' efficiency (stage **C**). The selected systems should be adequate for the analysed localization (climate conditions) as well as environmental-friendly. Traditional installations might be supported (or, in some cases, fully substituted) by renewable energy systems (stage **D**). The assortment of the available system highly depends on the localization (climate), but also local regulations as well as the closest area development plan. The potential improvement of building' energy-efficiency from stage **A** up to stage **D** is extraordinary, nevertheless, it might be increased even more. The application of **B**uilding **M**anagement **S**ystem (BMS) might furtherly reduce building's energy consumption (stage **E**). Those types of management systems operate the building, in such a way, that it has no impact on exacerbating the indoor climate quality but at the same time provide measurable profits. It is a common practice, to perform the stages **D** and **E** as a single modernization. As a result of correctly performed building modernizations, we might obtain energy-advanced buildings, which are a basis to establish **E**nergy **F**lexible **U**rban **A**reas (EFUA). Additionally, it is important to remember, that building modernizations should be a compromise between financial and environmental benefits, even with slight-edge for ecological aspects (see more in section **2.5**). The existing buildings' retrofitting is crucial for the environmental importance – the impact of environmental damage from new buildings is negligible compared to the existing ones, which were not refurbished.

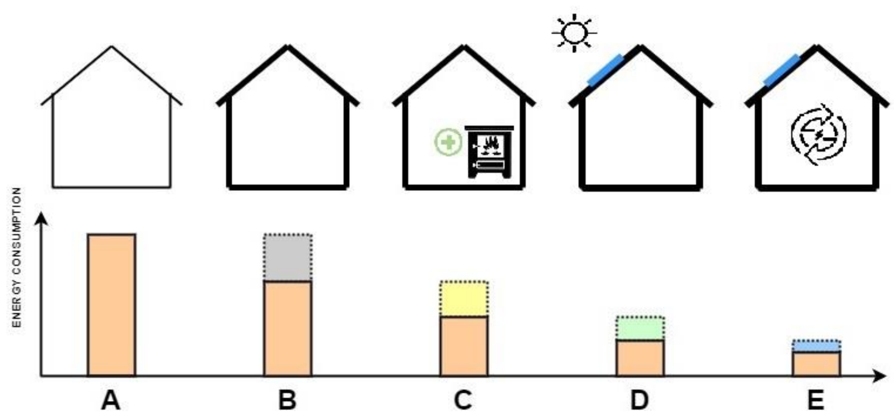


Figure 2.19. *Step-by-step schema on how to improve building' energy efficiency (own study)*

It was already mentioned, that todays' buildings can be designed not only as energy-efficient but also in accordance with the more advanced standards, such as **N**early **Z**ero-**E**nergy (NZEB), **n**et **Z**ero **E**nergy (nZEB) or even **P**lus-**E**nergy (PEB). Each of the above-mentioned building types is typically defined with the primary energy demand (Q_p) [328]. The definition of nZEBs is very simple – these are buildings which have the annual balance of 0 kWh/m^{2}a of primary energy use (energy self-reliant building). NZEBs are less efficient compering with nZEBs – therefore, the annual balance of primary energy is greater than 0 kWh/m^{2}a. Finally, the PEBs are characterized by a negative annual balance of primary energy – that type of building produces surplus energy. The design process of PEB is extremely comprehensive and its' systemization was proposed by the *Fraunhofer Institute for Building Physics* (IBP) [384]. It is obligated to start with a structural and construction design, followed with an appropriate, high-end facilities assortment. After that, all the loads related to household appliances and building management should be analysed and optimized. At the very end, we should consider the application of RES in order to maximize the potential outputs and analyse how to make use of them.

Presently, there is a unique type of objects, commonly called **S**mart **B**uildings (SBs). The SB idea is based on the management of indoor parameters and energy consumption optimisation. Those type of buildings have a unique ability to become an energy prosumer as an active element in the urban infrastructure. SBs are usually equipped with a BMS allowing to control building installations as well as on-going communication with a grid. As a result, SBs might be a starting point in introducing a new concept of energy flexibility within an urban area. **E**nergy **F**lexible **B**uildings (EFBs) are superb technologically-advanced objects, whose biggest advantage is an ability to manage and control their energy demands. EFBs are extremely useful in terms of management of a local urban grid, as well as they might be a successful response to changing climate conditions. The newest undergoing transformation of buildings towards energy flexibility was defined in 2018 (see **Figure 2.20**). It can be concluded, that with further improvement in the energy efficiency of buildings we are getting closer to reach the goal of energy independence as well as environmental harmlessness in built environment.

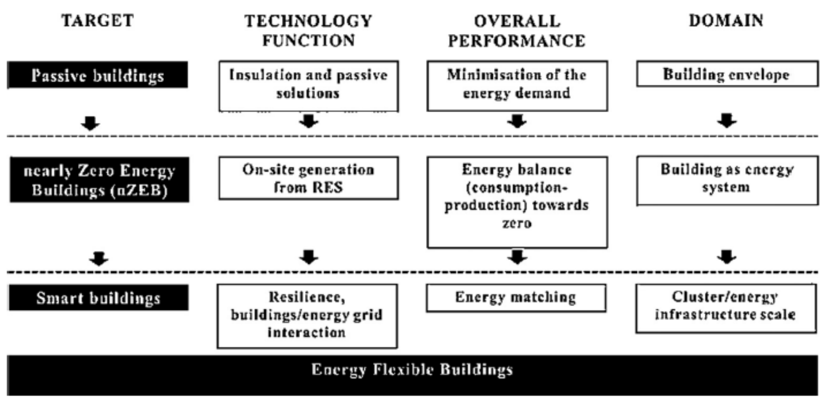


Figure 2.20. *The undergoing transformation of buildings towards energy flexibility (source: [261])*

There is an interesting alternative on how to measure building energy efficiency. The attractive concept of an **E**fficiency **H**ouse **P**lus with **E**lectro-mobility (EHPE) was firstly constructed in Berlin, Germany, in 2012 [291]. The idea is based on the increased popularity of e-vehicles; therefore, buildings could become charging spots for that kind of automobiles. The concept of EHPE includes building design following the PEB standard. The surplus energy generated by usage of RES would be used to charge an e-vehicle. The efficiency of EHPE is measured with the distance, which an e-vehicle could travel being charged with the electricity produced by the specific building. The pilot model of EHPE located in Berlin is presented in **Figure 2.21**. It looks like the EHPE building type will become more and more popular in the nearest future. It is also expected, that those type of buildings will improve urban-energy transformation into EFUA.

Numerous researches about energy-advanced buildings have been already made – some of them can be found in [23], [37], [43], [137], [170], [171], [199]. All researchers agree, that the development of those types of buildings is crucial to protect the natural environment. Unfortunately, refurbishments of existing buildings up to the highest energy standard might be financially unprofitable.

Figure 2.21. *Efficiency House Plus with Electro-mobility in Berlin, Germany (source: [291])*

There is a unique type of the existing building stock – the historic and traditionally constructed buildings, which has a significant impact on the energy consumption within the whole sector as well as it requires a specific treatment during retrofitting [264]. The historic buildings can be defined with three main attributes: the age (usually at least 50 years old), the integrity (maintenance of physical characteristics of the past period, decade or era) and the significance (by means of historical, cultural and/or aesthetic values) [178]. The traditional buildings might be defined as '*buildings of traditional construction with permeable fabric that both absorbs and readily allows the evaporation of moisture*'. Typically, the traditional buildings are characterized by the year of construction and/or their envelope construction. The both types of buildings are quite similar but they are not interchangeable. The necessity of analysing both historic and traditional buildings is essential because they account for at least 10% of the building stock (share up to 40% depending on the region) [138]. Typically, conservation officers are reacting negatively on potential retrofitting of the historic or traditional buildings, due to the possible threat of damaging historic fabrics. Nevertheless, up-to-date researches proved, that the energy retrofitting of historic and traditional buildings are now seen as an opportunity to protect those buildings, simultaneously responding to the global environmental trends.

Having a closer look on the proposed schema on how to improve building energy-efficiency (see **Figure 2.19**) it can be concluded, that no matter the building type, the procedure remains the same, while the applied technologies and modernizations solutions varied. In the text below a more detailed overview of each stage is presented.

The stage **A** is based on building' examination and its' base energy-efficiency assessment. The analysis should be performed as comprehensive as possible, in order to minimize all potential deviations comparing with a real state of the building. The complexity of the performed examination is based on the knowledge and experience of the executor, as well as it is determined by the local regulations. As the result, a specialist document (report) is elaborated, marking the energy profile of the analysed building. Those type of analyses should be performed at least twice, for the base and modernized variants in order to estimate the financial and environmental profits. The official documents which include all the above-mentioned aspects are called *Energy Audits* (AEB) or *Energy Efficiency Audits* (AEE) – in Poland, they are defined in [337], [340], [344]. In Poland thermal-renovation (stage **B**) is continuously the most popular solution to improve the energy efficiency of the national residential stock, following the local regulations [336], [341]. Additionally, equipment upgrades, adopting more efficient HVAC systems or replacing inefficient lighting systems (stage **C**) are also popular. Unfortunately, the more advanced methods such as RES applications (stage **D**) or building energy management (stage **E**) are still unappreciated, nevertheless, they might generate a huge environmental and financial profitability.

The stage **B** is referring to building enclosure modernizations. Building enclosure can be divided into two main groups of elements: the transparent and opaque ones. The opaque elements are walls, ceilings, roofs and floors, which renovation is typically based on adding a thermal insulation layer or renovating an exterior layer, in order to increase thermal resistance (R-value). The R-value describes how well the analysed partition resists a heat flow (q), which is usually expressed by the *Fourier* law [8], [13]. The U-value is the inverse of R-value and the both parameters can be used interchangeably. Both the thermal resistance (R) and thermal transmittance (U) can be calculated according to [358]. In practice, we are looking to minimize the heat flow through the building enclosure by means of increasing its' thermal resistance. For the above-mentioned modernization purposes, thermal insulation materials are used – they are characterized with a low thermal conductivity (λ) value, typically clearly below 0.10 W/mK (the lower the value the more efficient material is) [136], [205]. Typically, the thermal insulation layer is placed outermost, apart from when it is impossible (like in historical buildings). The comparison of different insulation materials (the traditional and advanced ones) can be seen in **Figure 2.22**. The more advanced material, with lower thermal conductivity, the lower thickness is needed to fulfil the required insulation level (expressed with the R-value). According to [205] one classifies the most used insulation materials into the following groups:

- inorganic materials (foam glass, glass-wool and stone-wool),
- organic materials (expanded and extruded polystyrene, cork, phenolic foam or cellulose),
- combined materials (gypsum foam or wood-wool),
- new technology materials (transparent materials, aerogels, vacuum insulation panels or dynamic insulation materials).

The traditional insulation materials, such as **E**xpanded **P**olystyrene **S**tyrofoam (EPS), E**x**truded **P**olystyrene **S**tyrofoam (XPS) and **M**ineral **W**ool (MW) are clearly the most popular for buildings applications [19], [116], [205]. EPS is typically used as exterior walls' insulation, XPS as an undercoat and thermal insulation of floors, ceilings and flat roofs, while MW is mostly used for slope roofs insulation as well as in wooden-frame houses. Typically, the thermal conductivity values of those traditional insulation materials are in the range of 0.03-0.04 W/mK.

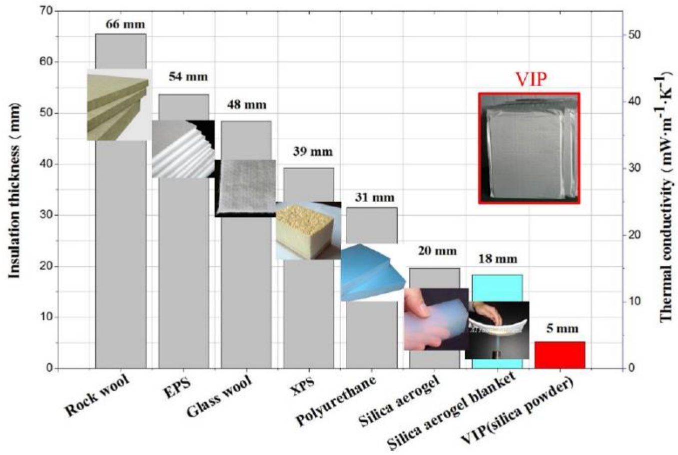


Figure 2.22. *Comparison of thermal properties of different types of insulation materials (source: [157])*

Aerogels and **V**acuum **I**nsulation **P**anels (VIPs) are two main novel insulation materials, which are of a high interest in research and development works. Aerogels and VIPs are commonly considered as superinsulation materials due to their remarkably good thermal properties. They are often known as solid air, or as the lowest density solid. Commercially available aerogels have thermal conductivity in the range of 0.013-0.014 W/mK. The up-to-date overview of the application of aerogels as thermal insulation in buildings can be found in [31], [62], [63]. Additionally, one of the biggest advantages of aerogels is their transparency – it seems like aerogels have a huge potential to start a revolution in windows technologies. According to [34], VIPs can be defined as '*an evacuated foil-encapsulated open porous material as a high-performance thermal insulation material*'. Typical VIP has three main components: core, barrier envelope (coating) as well as getters and desiccants [16]. VIP are extraordinary insulation materials, due to vacuum inside the core. The commercially available VIPs have thermal conductivity as low as 0.004 W/mK. VIPs have been already successfully applied in civil engineering and transportation. Nevertheless, VIPs are still under continued development, due to several concerns in their casual applications. They are very fragile materials. Also their high ageing-factor is still not fully understood, as well as VIPs have a significant decrease of thermal properties on their edges – we can observe the thermal bridges at joints of several panels. A detailed up-to-date overview of the VIPs can be found in [16], [34], [116], [127], [349], [350]. Still, VIPs might become an insulation material of the future.

There is a special type of materials, which cannot be classified as traditional thermal insulation, they are named as **P**hase **C**hange **M**aterials (PCMs) [74], [126]. The special feature of PCMs is their ability to store and release energy, opposite to the traditional insulation materials, which thanks to their low thermal conductivity (λ) reduce heat transfer. Therefore, PCMs received considerable attention for their application within the building envelope. The main feature of PCMs is based on their ability to utilize the latent heat of phase change, to control the temperature and heat flow. The mentioned phase change occurs in the specific range of temperatures, different for each PCM. Whenever the temperature rises above a specific point, the material will absorb the heat in the endothermic process. When the temperature drops, the material will return to solid-state and therefore release previously gathered energy. Typically, the range of temperature of phase change is around the desired comfort room temperature. Therefore, the application of PCMs leads to a reduction of energy usage, a stable and comfortable indoor climate (by smoothing out the temperature oscillations), as well as a reduction or shift in peak loads [32], [120], [144]. We can specify three main types of PCMs, accordingly organic, inorganic and eutectic [216]. Typically, PCMs are used in various fenestration products, especially within the innermost layer of walls or ceilings [181]. Several reviews on the PCMs potential application into buildings (including fenestration) were performed in recent years [66], [99], [133], [148], [240]. The detailed information related to PCMs can be found in the book written by Kosny [6]. PCMs are especially profitable in buildings with low thermal mass, where they can provide an increase in heat storage capacity. Also, the dissertation author made some analyses of PCMs application in commercial buildings [279], [280] – in both cases, the application of PCMs was beneficial in the analysed contexts. It is likely to increase PCMs application in buildings in the coming years.

There is also one more approach, related to building enclosure, which might result in the energy-efficiency improvement. It is based on building enclosure thermal mass, and its' ability to store and release of accumulated heat [154]. The selection of appropriate building thermal mass should be performed during the design stage following the object use. The thermal mass (*i.e.* thermal capacity) is usually associated with the mass of used materials – typically, the heavier material is, the higher thermal mass it has (except of PCMs). Therefore, the selection of proper materials should be considered to minimize building's heating energy consumption. Typically, whenever a constantly occupied building is designed, a heavy construction is more beneficial. On the other hand, whenever a periodically-occupied building is considered (such as holiday cottage) a light construction seems to be more appropriate. Additionally, it is important to remember, that the thermal mass of the building enclosure needs to be analysed simultaneously with its' thermal transmittance. Numerous studies related to the impact of thermal mass on the overall energy profile of buildings were performed – some of them can be found in [80], [219], [252].

The transparent parts can be renovated in two ways: usually by replacement of the whole element (*e.g.* window) or by adding some element (such as a low-efficient film or solar shadings), which will improve the component. Windows are a specific part of building enclosure, which are source of both, heat losses and solar gains. Additionally, windows are responsible for the biggest energy losses among building envelope elements, due to their relatively low thermal performance [64]. The heat losses through windows are particularly noticeable in the office buildings, where the share of losses can reach up to 45% [94]. Thus, it is extremely important to optimize the thermal performance, area and placement of the transparent components on the building's façade. There are the two main parameters of windows, which affect a buildings' energy balance: the overall heat transfer coefficient (U-value) and the **s**olar **h**eat **g**ain **c**oefficient (SHGC). Both parameters highly depend on the window construction – for the traditional windows, there is a correlation between the both parameters (typically, whenever U-value goes down, the SHGC also decreases). There are numerous types of windows, which are characterized by various features and application purposes. As usual, the more technologically advanced window, the more expensive it is. It is extremely important to select the appropriate window type for its' dedicated purposes, to avoid an overpay. Each window has two main elements: a frame and a glass pane. The most important purpose of the frame is to stiffen the window construction, while the glass pane ensures visibility through it. The share glass-to-frame ratio (C-value) is typically ranged from 0.7 to 0.9. For most of up-to-date windows, the frame is the weakest window part according to their thermal properties – numerous researches are focused on the frame improvements [97]. Presently, we are using multi-pane windows, to increase their overall thermal performance. The gap between each glass pane is typically filled with gas – it could be the air (the less expensive option) or any of noble gasses like argon, krypton or xenon. There are numerous types of windows. Windows selection is not only limited based on their thermal performance but they are also providing lighting and visual comfort. Thus, it is important to select the appropriate window type, which will meet defined expectations. Several analyses were made to obtain a combination of a comfortable interior with an optimal design for cooling and heating loads. Those types of analyses are extremely important not only for the optimization of energy consumption but also to assure good daylighting and visual comfort for the room users [20], [91], [262].

We might classify the windows according to the four main criteria. The first group can be defined with the number of glass-pane layers. The traditional double- or triple-glazed windows [25], [265] are presently the most efficient type of windows, including both pricing and performance. The quadruple-pane windows [25] or even six-pane windows [145] have been already developed – objectively, this is not the best course of windows technology development. The second group are windows with the low-emittance (low-e) coatings or suspended films [64], [121]. The suspended films are very thin compared with the glass pane, and they are usually placed between the outer and inner glass panes. The main advantage of low-e materials is their ability to reduce heat transfer through thermal radiation [122]. Next group are the novel windows, which nowadays are not commonly used due to their high price. In this group, we can list vacuum, aerogel, PCM and photovoltaic glazing. Each of them has a unique parameter, which makes them highly promising solution for windows of the future. The vacuum glazing concept was firstly introduced in 1913 by *Zoller* [242] but it was not successfully constructed until 1989 [71]. Those type of windows is based on capturing vacuum, between two sheets of glass. The very thin '*layer*' of vacuum eliminates conductive and convective heat transfer [61], [195]. Similar to VIPs, the biggest concern is the durability of those type of windows. The aerogel and PCM glazing replace the traditional glass with advanced materials. The aerogels are presently one of the most promising thermal superinsulation materials, occasionally used for retrofitting of residential buildings [62], [63]. The extraordinary thermal performance simultaneously with the transparency of aerogels enable them to be applied in windows. The aerogels are very fragile and sensitive to water – therefore the aerogel glazing requires a protection against the water and tensile stress [84], [92]. The aerogel glazing is already successfully applied to buildings [85]. Thus, a perfect material for windows application should be similar to aerogels but more durable and with greater visible light transmittance. The PCM windows use their ability to absorb energy from solar radiation and ambient thermal radiation, and simultaneously the ability of efficient releasing of captured energy. Unfortunately, the phase change process is decreasing visibility through the PCM windows. The solar glazing (*i.e.* photovoltaic glazing) has the both properties, translucency of glass and solar cells ability of harvesting energy [64], [121]. Numerous researches have been made during the recent years, investigating the solar glazing [55], [119], [209]. The performed studies have shown that solar glazing is a highly promising path of window technology development. The last group of windows includes the so-called smart windows [46], [222] and self-cleaning glazing [184]. Those type of windows is especially useful in a commercial building, with a large share of windows (transparent area) in exterior façades. Those types of windows are not focused only on improving energy-efficient, but also on providing multiple additional conveniences. The most popular smart window type is electrochromic glazing [33].

The stage **C** is based on buildings' facilities improvements. Each building has an installation system, which is capable to modify interior climate conditions. Every building has different installations depending on its needs and the use of property. Usually, the commercial buildings have much more complex facilities (especially the HVAC and lighting systems) comparing with the residential buildings, where the SH and DWH systems are crucial. All building systems require proper management, maintenance, renovations and after some time replacements in order to ensure their efficient work. It is essential to perform analyses of the considered installation assortments to receive appropriate facilities for the analysed building and its purposes. The mentioned assessments, used to evaluate the efficiency and performance of different units, can be performed using the dynamic building simulation softwares (see more in section **2.7**).

Each type of building installation system works for different purposes. It is typically based on 3-steps schema, starting with the production of a '*medium*', its distribution and final usage. In a building context, the above-mentioned medium is usually heat, cold, air or domestic water (both hot and cold). Therefore, any system modernization might be performed comprehensively (all parts of the system together) or partly. As an example let's examine traditional SH in a residential building: we might replace inefficient heating stove (heat source), insulate or replace the piping system (circulation) or replace radiators (heat distribution). Obviously, for more complex systems a potential modernization become a more challenging task, nevertheless, the concept remains the same.

An up-to-date description of all types of HVAC system parts is a very difficult task due to numerous possible solutions as well as constant technologies development. The systems vary by their purposes, – there are different solutions for the residential and commercial buildings. Basically, all the HVAC systems can be divided according to the medium of energy distribution – there are hydronic (water-based) and all-air (ventilation) systems. For the hydronic systems, the main way of heat emission is by radiation, while for the ventilation systems by convection. The comprehensive description of most HVAC system parts and equipment can be found in the ASHRAE (**A**merican **S**ociety of **H**eating, **R**efrigerating and **A**ir-Conditioning **E**ngineers) Handbook [286]. According to the above-mentioned reference, we might define the following groups and components of HVAC systems:

- air-conditioning and heating systems,
- air-handling equipment and components,
- heating equipment,
- cooling equipment,
- general components,
- packaged, unitary and split-system equipment.

The main purpose of HVAC installations is to provide a comfortable indoor environment for building occupants [201]. Therefore, the building energy consumption is influenced indirectly by the occupants' comfort. The above-mentioned problem is the most challenging task for building designers – the primary goal should always incorporate minimal energy usage (cost-optimal solution) while maintaining suitable indoor thermal comfort conditions [39], [69]. The comprehensive overview of HVAC systems in buildings applications can be found in [286].

The stage **D** refers to applications of RES into buildings. In the last two decades, a great progress has been made in the field of renewable and sustainable energy, but still more work needs to be made to increase the renewable energy share worldwide. It can be pointed out that only in the last 10 years, the world energy demands have been doubled. According to the EIA [426], the global energy consumption is expected to increase approx. 1.4 % per year. This situation put more pressure on scientists and communities to work harder on increasing usage of RES. Within the RES we can define sources which are generated by harnessing a natural process (energy produced out of solar, wind, geothermal, water or oceans), or by using mechanical devices (usage of biofuels and hydrogen). The RES commonly used for buildings applications are solar, wind, geothermal and biomass. The most popular renewable energy technologies used for buildings applications are solar collectors (solar thermal systems), **P**hoto**v**oltaic (PV) panels, **G**eothermal **H**eat **P**umps (GHPs), wind turbines and biofuels systems (heating boilers).

It is important to remember, that before any renewable systems implementation into the buildings following factors should be considered:

- available nearest building site and conditions for the installation application,
- cost of energy from the energy providers (alternative energy sources),
- installation and maintenance costs,
- local regulations,
- impact on the local architectural and natural environment.

The renewable energy technologies application into buildings will be profitable only if we considered them during the last stage of buildings' design or their refurbishments (after the stages **B** and **C**). The used technologies should be in accordance with the buildings' design and their operations. The RES systems might be an extremely successful solution used to offset buildings energy consumption (either electrical or thermal).

Solar energy enabled the usage of renewable energy sources for small buildings' applications. The potential of solar energy is usually measured by means of the local solar conditions, using the irradiation data. The territory of Poland is characterized with rather average solar conditions, with the yearly sum of irradiation in the range 950-1150 kWh/m^2 [381]. Nevertheless, those type of systems are still profitable. Solar energy might be used in active or passive way [2]. The passive methods use sunlight without any active mechanisms (*e.g. Trombe* wall) as contrasted to the active ones, with conversion of sunlight into usable heat (solar collectors) or electricity (PV panels). The solar system used for electricity production can be either connected or disconnected to the local electric grid. Thus, we can define the on-grid (grid-tie) or off-grid (stand-alone) systems. Selection of the appropriate model is crucial for correct solar system work, which will be able to fully use the generated electricity. Whenever we select the on-grid system we can trade the surplus produced electricity with a local distributor. The off-grid systems require batteries (described further in this section) in order to store the surplus produced electricity. The stored electricity can be used whenever it is needed, later on. It is also possible to apply a hybrid system (a combination of the both on- and off-grid systems), then we are allowed to either stored or trade the surplus produced electricity.

Solar collectors are simple products, used to collect and accumulate heat out of solar radiation. In solar collectors an absorber (usually water, sometimes a water-glycol solution in order to avert freezing) is heated to produce hot water (DHW systems) or hot air (DH systems). In practice, the solar collectors are a successful technique used for DHW systems in residential buildings (especially in single-family houses). The various types of solar collectors were introduced in [129]. An up to date overviews of solar collector applications into buildings can be found in [2], [11], [77], [129], [254]. PVs are probably one of the most promising renewable energy technologies. We might say, that PVs allows producing electricity directly from the sun without any concern for energy supply or environmental harm. Whenever light shines on the solar cell (panel) it creates an electrical field across the layers, causing electricity to flow – the greater the intensity of the light, the greater the flow of electricity. The up-to-date overview of different PV technologies types can be found in [217]. The PVs technology is probably the fastest developing type of RES systems – in

Figure 2.23 the timeline of different PVs technologies development and their efficiencies are presented. The up-to-date overview of PVs applications into buildings can be found in [83], [239].

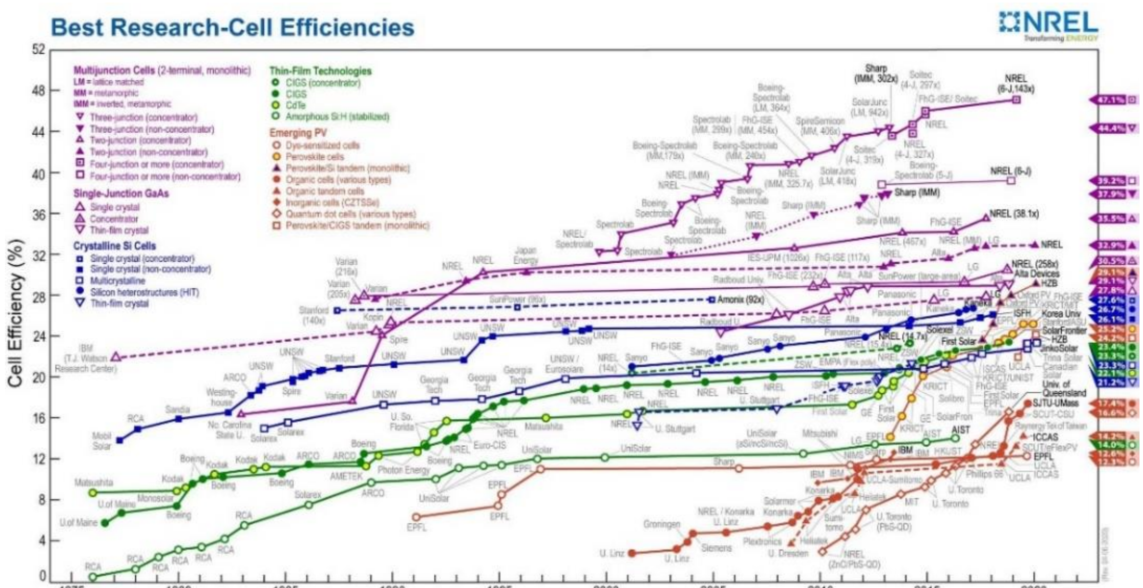


Figure 2.23. *A timeline for best research-cell efficiencies for various PV technologies (source: [416])*

The present technology allows us to use solar energy by amalgamating features of the solar collectors and PV – it is possible due to **P**hoto**v**oltaic-**T**hermal (PVT) systems [22], [276]. An additional advantage of solar energy is its flexibility in potential integration into the building envelope. It can be used in a traditional way (a type of montage) or as integrated part of buildings. Numerous researches have been already made focusing on **B**uilding **I**ntegrated **P**hoto**v**oltaic (BIPV) systems [117], [118], [119], [256]. The detailed explanations, definitions and basis related to the solar energy, as well as solar systems can be found in [2], [11]. More about methods on how to estimate the potential output out of solar systems can be found in subsection **3.7.4**.

Wind energy is the second among the most popular RES used in buildings. The wind is defined as an air movement from the area of higher pressure to the area with lower pressure. The wind energy might be practically used thanks to wind turbines; we can distinguish the horizontal and vertical ones (see **Figure 2.24**). The typical wind turbines are horizontal – they are normally characterized with a large, 3-blades rotor and impressive sizes (in most of the cases above 100 m tall). The **V**ertical-**a**xis **W**ind **T**urbines (VAWT) are usually more compact, with very different shapes of rotors – they can be mounted directly on buildings. It can be concluded, that the horizontal wind turbines are more beneficial for the whole area purposes, while the small vertical ones are suitable for the local, single building applications. The profitability of wind turbines applications is highly related to the local wind conditions. The **H**orizontal-**a**xis **W**ind **T**urbines (HAWT) are successfully applied onshore, as well as offshore – where the wind conditions are much more profitable. The comprehensive classification of wind turbines is presented in **Figure 2.25**.

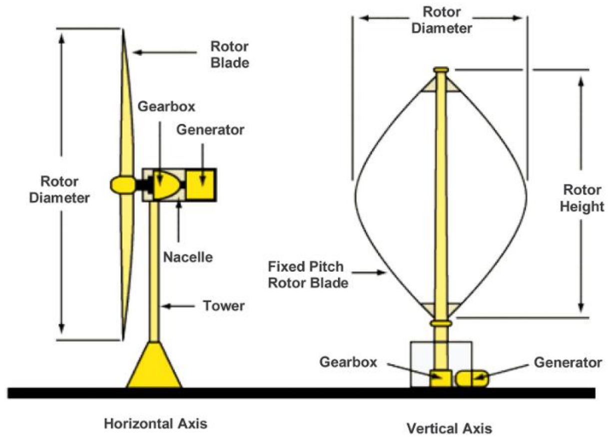


Figure 2.24. *Type of wind turbines and their basic constructions (source: [1])*

The fundamentals of how wind turbines work is rather simple – it is based on *Betz's* law, concerning conversion of the wind kinetic energy into mechanical energy. The potential of electrical power production by the wind farm depends on several parameters, accordingly the turbine geometry, its' power coefficient (C_p) and wind conditions. The C_p value is unique for each turbine and is a function of the wind speed that the turbine is operating with – according to *Betz's* law, the potential maximum value is 0.593. In fact, there are some additional losses of efficiency, causing its decline (*e.g.* rotation of the wake behind the rotor or aerodynamic drag) – thus typically the C_p value is between 0.35 and 0.45 [1], [10].

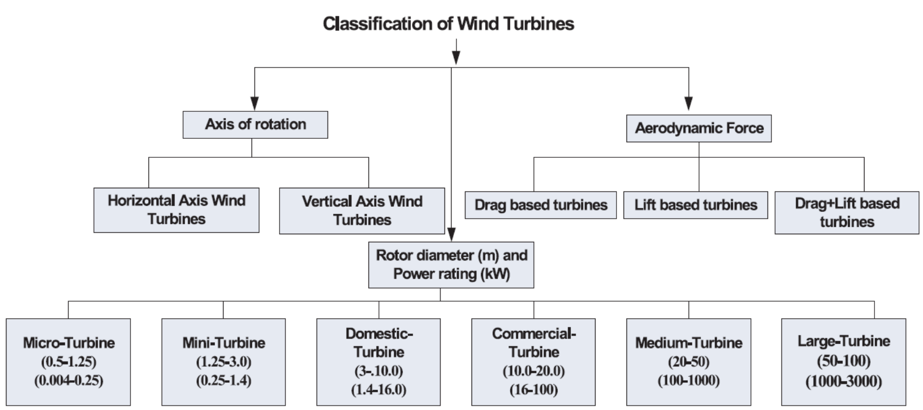


Figure 2.25. *Classification of wind turbines (source: [147])*

The wind turbines technology is constantly developing and searching for new solutions. Even when the answer to the question where to expect a sufficient wind potential is simple, the new ideas are constantly appearing. Presently, many studies are concentrated on **B**uilding **I**ntegrated **W**ind **T**urbines (BIWT) concept [112]. The BIWT concept might be a milestone in **U**rban **W**ind **E**nergy (UWE) development as well as an improvement of the urban environment. The comprehensive review on wind turbines and their applications can be found in [30], [112].

Geothermal technologies use the heat from the centre of the earth – which is a practically unlimited source of heat. Starting at approx. 10 meters below the earth's surface, almost everywhere ground (or groundwater) maintains a nearly constant temperature close to the yearly average air temperature. The geothermal energy can be used directly or by GHP, which during previous two decades have been widely applied into numerous buildings. The ground of constant temperature is used by GHP systems as a source of heat. Thanks to the GHP systems it is possible to use this heat to provide energy from heating and cooling purposes in buildings. We can define different types of GHP based on their heat source and the heat or cool distribution fluid [228]: air-to-air (the most common type), water-to-air, water-to-water, ground-coupled. The selection of the most appropriate type of GHP system should be considered based on the factors like, the climate and soil conditions, land availability and costs. The all types of GHP are characterized by a very good performance, with the average value of COP equal to 3.6 for central European countries [311]. There are no limitations regarding dependency between GHP systems and building type while their applications' number rises each year due to the surge of green buildings [36]. A typical GHP system consists of a heat pump, ductwork (air delivery system) and heat exchanger. The mentioned heat exchanger systems can be buried in the ground using vertical or horizontal geometry [161], [273]. An additional advantage of the GHP systems is that it can provide heat recovery – heat removed from the indoor air (typically in summer) can support the DHW system. Additionally, the GHP systems can be combined with a solar system providing a very efficient hybrid system, perfect for the energy-advanced buildings [263], [273]. Application of the GHP system in buildings impose a complexity related to buildings' construction and installation design, which require careful considerations. The ability of combined heating and cooling application is an energy and cost-effective solution for the GHP technologies applied into buildings. Nevertheless, the GHP is the most expensive type of RES for building applications. More information about the technical parameters, applications and guides related to GHP systems can be found in [9].

Biomass is a plant or animal material used as a fuel to produce electricity either heat. The biomass releases CO_2 during burning (*i.e.* energy generation process), nevertheless, it has still been classified as a RES due to the fact, that it captures more CO_2 during the short-cycle growth than during the burning process. The term '*biomass*' involves a large variety of materials, such as wood, agricultural deposits, and animal and human waste. As a bioenergy source, we can distinguish the biomass, biogas and biodiesel. Typically, the biomass is used in the domestic sector (as firewood or pellet), followed by biogas and biodiesel, which are more commonly used as a vehicle's fuel. The biomass can be produced using one of the following methods: thermal, chemical, biochemical or electrochemical conversions. Typically, the biomass is used as a supply fuel for the small systems in residential buildings; it can be used in both, DH and DHW systems. Those systems are mainly composed of the stoves (usually supplied by pellet and wood), ducting exhaust system (like a chimney) and supply piping. After all, the biomass-based heating systems are similar to the traditional, fossil-fuel DH systems. The biomass as a RES has an amazing potential – out of all the RES bioenergy has been identified as the most important and promising one for Poland [196]. It seems like due to the cost-advantage and availability of the bioenergy, it will be the major contributor towards sustainable development of Poland, following targets such as EU 2020 plan [332]. The further researches related to biomass and its application can be found in [72], [153].

In the end, it should be pointed, that there are three major disadvantages of RES in the building applications. The first one relates to the cost of the system– in most cases, it is more expensive than the traditional one. The second drawback relates to much more complex availability, the required conditions and legal regulations. It might be surprising since RES are omnipresent, nevertheless, numerous factors need to be checked before their application. Thirdly and mostly, the RES are unpredictable as well as time and location dependant – there is a high risk of potential lacks of energy supply for facilities supported only by renewables. Wherefore, to obtain a reliable renewable energy system a comprehensive analysis should be performed, including management on timely-basis demands.

The stage **E** refers to the building energy management, in order to optimise the overall consumption. The proper management allows to received sufficient profits without significant financial contributions. The only disadvantage of the system is a necessity of monitoring the actual interior climate to assure the appropriate conditions for occupants. The above mentioned requires the knowledge and experience in the field of BMS applications. Additionally, presently it is hard to find a novel HVAC system or system based on the renewable source which has no steering module. Therefore, it is a common practice, that the stage **E** is usually partly included in the stage **C** or **D** of building’s modernization.

BMS, otherwise known as **B**uilding **A**utomation **S**ystem (BAS), can be defined as a control system that can be used to monitor and manage the mechanical, electrical and electromechanical services in a facility. Therefore, the BMS is capable to control services such as the HVAC systems, physical access control, pumping stations, water treatment, elevators, lights, servers, office equipment as well as security systems. Numerous studies both experimental as well as based on measured data were already performed [70], [234] – those analyses confirmed, that BMS is an effective approach in buildings energy-efficiency improvement. Also, a **B**uilding **E**nergy **M**anagement **S**ystem (BEMS) is getting more and more popular – it is the section of BMS, which is fully focused on the building energy consumption [168].

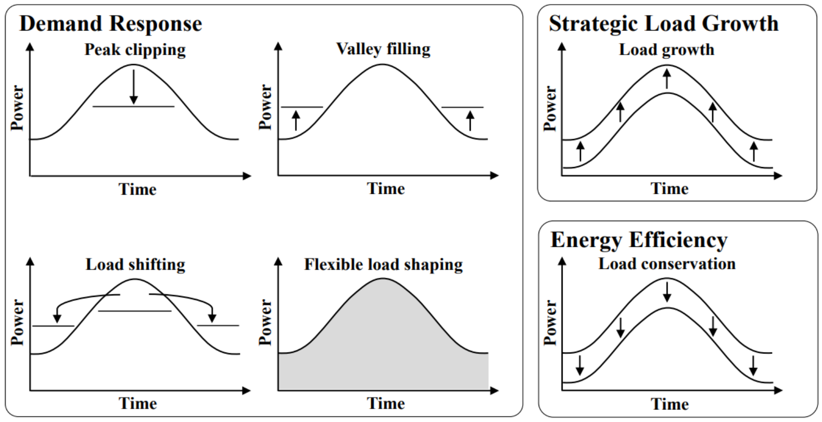


Figure 2.26. *Categorization of DSM techniques (source: [150])*

Among the numerous strategies of BMS, one is extremely efficient in terms of the potential energy-savings. Application of the so-called **D**emand **S**ide **M**anagement (DSM) techniques fulfil the basis of BMS as well as BEMS. The DSM was firstly introduced in the late 70s; according to [150]: '*Demand-side management encompasses the entire range of management functions associated with directing demand-side activities, including program planning, evaluation, implementation, and monitoring*'. Numerous approaches of the DSM are used to shape the time-distributed load demand – the basic categorization of DSM can be seen in **Figure 2.26**. Those techniques are extremely efficient because whenever the analysed building has BMS, the cost of DSM application is marginal, contrasting with the potential profits. Some exemplary studies on the DMS techniques in buildings applications can be found in [88], [132], [182], [259].

Increased interest and investments for the exploitation of highly efficient RES [176] require a novel approach to make full use of the produced electricity. High-efficiency energy storage systems (batteries) are practical solutions applied in tandem with RES, in order to use most of their energy-productiveness potential. The battery systems can efficiently store and deliver energy on demand, therefore they are an efficient method to improve the power quality and load management [142], [250] of local electrical grid. Therefore, a local mix of energy storages and renewable energy systems improves the electrical grid considering its flexibility, safety and reliability. The batteries constantly are becoming a more and more popular part of the high-tech residential renewable energy systems, especially for the photovoltaic and wind energy systems [232]. The storage technologies can be divided into five groups, based on the form of energy stored, as follows: chemical, electrical, electrochemical, mechanical and thermal. Each technology has its unique characteristics, different prices and are in different implementation stages (see **Figure 2.27**) – some of them are under the research and development phase, while the others are commercialised (widely available). Unfortunately, the energy storage technologies are still in the early stage of development [146]. Application of the batteries into buildings systems is extremely helpful in order to appropriate energy-management. Some overviews of commercially available energy storages systems, such as the '*Powerwall*' [400], used for residential purposes were analysed in [223], [257]. The detailed overview of the studies concerning the battery storage is shown in [108].

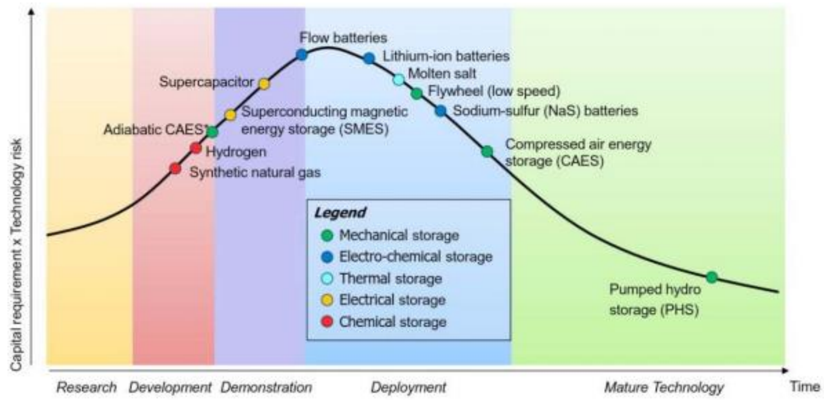


Figure 2.27. *Energy storages systems overview and their development stage (source: [302])*

A successful application of the batteries working with a PV system is presented in **Figure 2.28**. The graph shows schematically the hourly electricity generation (out of the PV system) and consumption for the one-day period. It was assumed, that the system uses PVs outputs whenever they are sufficient to encompass the current electricity demand (**4**). The electricity generation exceeding over the actual demand is either stored (**2**) or sold (**3**) into the grid. Later on, the stored electricity can be used (**5**), especially during the day-time, when the electricity prices are the highest. The above-introduced procedure can be considered as an effective active DSM technique, appropriate especially for the both residential, as well as commercial buildings.

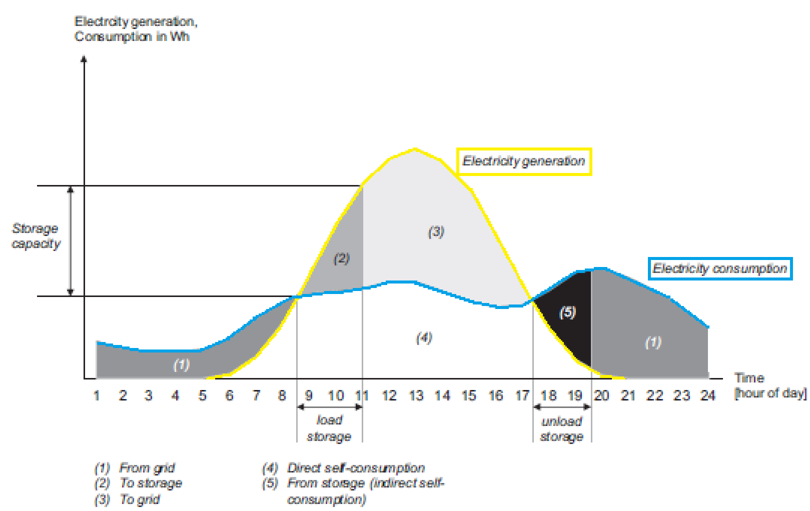


Figure 2.28. *An exemplary distribution of hourly electricity demand for an on-grid PV system with batteries (source: [108])*

One more aspect needs to be discussed whenever building modernizations are considered. Every time whenever we are influencing building enclosure as well as its' facilities, we should also care about the indoor climate conditions. Even the most profitable refurbishments variants in terms of the economy and environmental aspects, which are not meeting the required indoor environment conditions are unaccepted for application into buildings, which are intended for the permanent stay/work of people. Therefore, we should always perform a thermal comfort analysis whenever we are modernizing buildings. The thermal comfort has been debated since the 1930s, and according to [327] it can be defined as a *condition of mind which expresses satisfaction with the thermal environment*'. There are two main models of thermal comfort approaches: the steady-state and the adaptive one. The adaptive approach is mostly based on the concept of the human body's adjusting to the outdoor and indoor climates. The most popular steady-state approach of thermal comfort analysis is the model developed by *Fanger* in 1970 [4]. As the result of multiple types of researches, the index called **P**redicted **M**ean **V**ote (PMV) was derived. The PMV index is a function of the following variables: air temperature (θ_a), mean radiant temperature (θ_{mr}), relative air velocity (v_a), air humidity (p_a), activity level (M) and clothing insulation (I_{cl}). The PMV index is expressed with the value within the seven-point thermal sensation scale, where -3 means intolerably cold, -1 – slightly cool, 0 – neutral, +1 – slightly warm and +3 – intolerably hot [4]. We should aim to design the building's indoor conditions which are acceptable to at least 80% of the occupants – this requirement corresponds to the PMV in the range from -0.5 to +0.5. The empirical relationship between the PMV (sensation scale index) was defined, to obtain the so-called **P**redicted **P**ercentage of **D**issatisfied (PPD) [271]. The relationship between the both indexes (PMV and PPD) is illustrated in **Figure 2.29**.

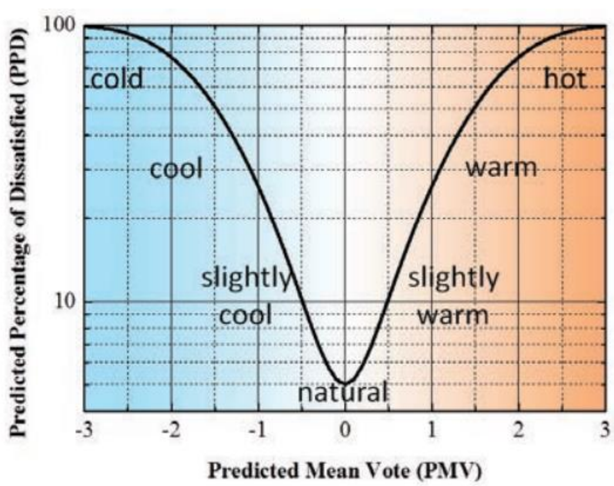


Figure 2.29. *Relationship between the PMV and the PPD indexes (source: [230])*

The thermal comfort analyses are a popular topic for dozens of researches, with the peak popularity in years 2008-2014 [224]. In order to obtain a comfortable environment, it is also obligated to ensure an appropriate air quality, especially with the relatively low CO_2 concentration. Lastly, whenever the thermal comfort is considered it is also recommended to analyse other components of a residents' comfort – the visual and acoustic aspects. According to [351], visual comfort is '*a subjective condition of visual well-being included by the visual environment*'. Acoustic comfort can be defined as '*a state of contentment with acoustic conditions*' [192]. Both aspects, the visual and acoustic comforts were discussed in [24], while a very interesting ranking of the importance of different environmental conditions (air quality, thermal, visual and acoustic) for overall occupants satisfaction was presented in [79].

CONCLUDING REMARKS

Each building is unique with different characteristics. The retrofit techniques used in one building may not be suitable for use in another building. During the design stage, we should analyse the best solutions in order to maximize passive energy-savings. The impact of the localization (climate conditions) as well as the building orientation cannot be neglected. Also, the heating and ventilation design is crucial in terms of defining the buildings energy characteristics. The above mentioned parameters have a significant impact on the buildings' energy consumption, especially the heating and cooling loads.

Thermal insulation is a major part of the complex structural elements which form the building's shell. Nowadays, we are constantly increasing thicknesses of the insulation layer or replace traditional materials with the novel ones. Increasing thermal insulation is still the most popular and easiest way for the improvement of building's energy profiles. Additionally, it remains the most cost-effective way toward the energy-efficient buildings.

Windows are a very important part of building enclosures – they are unique, transparent components necessarily needed to obtain the visual comfort of the building residents. The windows are also exceptional because they are simultaneously heat gainers and losers. Therefore, the selection of windows should be based on a complex assessment. Presently, the double- and triple-glazed windows are the most popular, frequently with application of a low-e coating. Nevertheless, it looks like it is just a matter of time when we will reach a revolution in the windows technology – the traditional glazing will be replaced with some novel technologies such as the vacuum-glazed or aerogel windows.

Buildings' installation systems should always be selected in order to meet the requirements of indoor conditions. Those requirements are directly linked with the thermal, acoustic and visual comfort of the building occupants. Ensuring the appropriate indoor conditions entail the higher energy consumption, therefore it is crucial to comprehensively analyse potential solutions to select the optimal one. We should always consider the highly-efficient and environmental-friendly HVAC systems, expanded with the management system. Additionally, whenever it is possible, we should apply some active DSM techniques to maximize the energy efficiency.

RES are without any doubts the future of energy sector for humanity. Their potential is unquestionable and basically unlimited – the present limitation in energy generation occur only due to the technologies imperfections (mostly caused by the low efficiency of available systems). All the disadvantages of RES are temporary, and will be overcome in the nearest future – the technology cost will be affordable, the efficiency will be higher as well as the legal regulations will be changed. Also, the RES are the obligatory factor in terms of sustainability – without their applications, the natural environment will be unconvertible damaged. Therefore, academic, research, engineering, industry and government communities are obligated to an intensive work on the RES.

The chase for highly efficient buildings is real and its validity constantly becoming more important. The energy efficiency improvement is a natural strategy for both, new and existing buildings. Right now, we are probably in front of a revolution of residential buildings' design – we are no longer looking only for minimizing the energy bills, but to become energetically independent. Unfortunately, those advanced strategies for the residential buildings of the future require many types of research before they become commonly available and financially affordable. Therefore, we are still performing refurbishments of the traditional buildings – from the typology of representative building stocks for the EU (consisting of 72 building types), it was obtained, that retrofitting is significantly effective, in the context of energy, financial and ecology profitability (especially in the Central and Northern Europe) [193].

Summarizing, the as much as possible energy-efficient concept of a building requires application of all the techniques presented in this section. A mix of the presented energy-efficient solutions is the only equitable approach toward designing the sustainable and energy-flexible buildings of the future. Architects and engineers are challenged during the building design process to meet the above-introduced requirements and regulations. The process is very complex including the social, economic, environmental, technical and aesthetic concerns. The energy efficiency concept became presently a major and inseparable concern of buildings' existence – nevertheless, it is a complex issue, due to diversity of buildings. Also, the actual building energy consumption is highly dependent on the inhabitants' behaviour, which is still an insolvable variable in the buildings energy-related analyses. Anyway, it is necessary to constantly implement some novel technologies into building design in order to improve their energy efficiency or furtherly aim towards the energy independent buildings.

2.5. TOWARDS BUILDINGS' SUSTAINABILITY – OVERVIEW

Nowadays, we are facing serious environmental problems, which have a significant impact on our life. Among various harmful environmental issues, the most important are the global warming, ozone layer depletion, droughts or waste accumulation. Those problems are typically related to the activity and technological development of humanity, particularly the energy consumption as well as its' production. Therefore, the energy consumption is strongly correlated with the natural environment.

Unfortunately, the environmental concerns are a quite new research field – in the past, those types of problems were neglected or had less attention. In the 1970s, the primary focus was on various energy and economics analyses, as well as the mutual dependencies between them. Nevertheless, the environmental problems and natural disasters occurring more and more frequently all over the world, become a motivation for the analyses focusing on sustainability. The academic community was the first one which has investigated the environmental concerns. It was quickly concluded, that the environmental problems are strongly associated with the greenhouse effect, which ensues due to the emissions caused by the fossil fuels burning. The most hazardous gasses, with the most environmentally harmful impact, are carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_x), as well as **P**articulate **M**atters (PM). The **S**ustainable **D**evelopment (SD) began to be popular after 1987 when the United Nations World Commission on Environment and Development (presently the **W**orld **C**ommission on **E**nvironmental and **D**evelopment – WCED) [423] published the report commonly called the *Brundtland Report* [321]. In the published report, the common and most widely recognised definition of SD has been proposed. According to [321], '*sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs'*. An interesting fact is that the well-known three-sphere framework (see **Figure 2.30**), which illustrate the SD concept, was initially proposed by *Passet* in 1979, long before the definition of SD was established. Those three pillars of the SD philosophy are the environmental, social and economic aspects. The main assumption following the SD idea is the ability to find a common part between the all three aspects.

Presently, numerous norms and regulations are referring to the concept of SD. The SD has a very comprehensive definition, which is concluded in [360], while each pillar is widely introduced in [361], [362], [363]. The economic pillar can be defined as a detailed cost analysis, which might be performed using the **L**ife **C**ycle **C**ost (LCC) method (see more in section **2.5.1**). The social pillar is based on all factors affecting the receivers and internal environments which surrounds them. In particular, it aims for the thermal comfort assuring (see more in section **2.4**) or the aspects like proper air quality, safety or acoustic comfort [366]. The environmental pillar is an assessment of the investment's impact on the environment, which might be performed using **L**ife **C**ycle **A**ssessment (LCA) analysis (see more in section **2.5.2**). The basis of the environmental pillar is related to the water treatment, energy demand control, renewable energy applications as well as materials management with their potential recycling or re-use [364], [365].

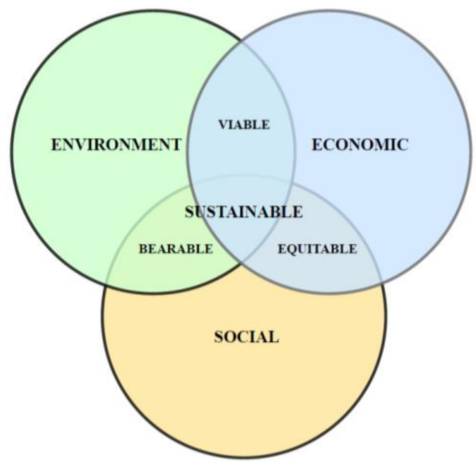


Figure 2.30. *The Sustainable Development conceptual schema (own studies)*

The **C**ircular **E**conomy (CE, commonly called circularity) is a new approach aimed at eliminating any wastes as well as implementing the continual use of resources (re-use ideology). The phrase was firstly introduced in the scientific report published in 2013 [289], followed by the standard (strategies and guidelines) established in 2017 [330]. In general, the major assumption of the CE paradigm is switching the current '*take-make-waste*' model into the positive society-wide benefits (a conceptual schema of the CE paradigm can be seen in **Figure 2.31**). The transformation can be obtained based on the three principles: limiting wastes and pollutions, constant (circular) use of products and materials as well as regeneration of the natural environment.

In the last few years, the CE is receiving growing attention worldwide, within the academia, industry and policymakers societies [90]. The major concern is related to the question, is the CE a new sustainability paradigm? Presently it is difficult to answer the mentioned question – it seems like the CE emerged from the SD paradigm [82], [87]. Nevertheless, according to the actual literature overview, the biggest barrier between using the CE and SD paradigms interchangeably is related to the impact of social aspects.

The concept of CE can be successfully applied to various types of investigations, including the building sector analyses. In [155] the tool to support the CE paradigm in the building sector was presented, including a 5-steps assessment:

- Phase 1: preparation & vision development,
- Phase 2: involves market & supply chain,

- Phase 3: process design & collaboration,
- Phase 4: business model & implementation,
- Phase 5: usage & prepare for the next use.

Figure 2.31. *A schematic concept of the Circular Economy paradigm (source: [375])*

The implementation of CE paradigm is still at an early stage of development. Nevertheless, the CE provides a reliable framework towards drastic improvements including preventive, regenerative and environmental-friendly development. Also, the CE model can be underpinned by a transition to the RES usage, resulting in the improvements in economic, environmental, and social assets.

The SD analyses are applied not only for various products but also modernizations and services. Each product can be made following the sustainable development standards, nevertheless, a suitable method is required to evaluate the whole process. The assessment method for sustainability analyses should include the environmental, economic and social impacts. Buildings are an inherent part of our life, therefore it is prescribed to build new objects in accordance with the sustainable development principles. In order to design the environmentally-conscious buildings, their impact on the environment during the entire service life must be known. Both of the above-introduced paradigms, *i.e.* SD and CE, have some accurate guidelines, which should be followed in terms of the future sustainability of humankind.

2.5.1. ECONOMIC ASSESSMENT METHODS

The economic analyses are crucial to validate the profitability of any project or modernization. Presently, there are numerous types of economic analyses, which are suitable for different purposes [27]. Within numerous types of economic analyses, the LCC method is the most comprehensive and the most reliable one. Nevertheless, other simpler methods are still very popular especially for the investors, who prefer a quick assessment of potential profits. The economic analyses performed for various studies on buildings modernizations are a popular topic of the scientific literature [159], [187]. In this section, the economic methods used in the analyses performed as a part of the dissertation are introduced.

The simplest method to validate the economic aspect of an investment is the **S**imple **P**ay-**B**ack **T**ime (SPBT). Although the SPBT method is very simple, this is still a very popular and recommended approach to evaluate the performed modernization [337], [340]. Using this method, we are receiving a number of years, which needs to pass to start obtaining profits (*i.e.* pay-back the investments). The simplicity of SPBT method is its' biggest advantage. On the other hand, the mentioned simplicity is also the biggest disadvantage of the SPBT method. Due to the key simplifications, it is impossible to include all the meaningful factors, which have a significant impact on the overall financial profitability. Those factors are especially, the up-to-date maintenance costs, potential repairs or replacements, as well as energy pricing and inflation. The SPBT is defined with the following equation, using the costs and profits expressed in the selected currency.

$$SPBT = N_U / \Delta O_N \tag{2.1}$$

The second method is called **N**et **P**resent **V**alue (NPV). In general, the NPV method is used to determine the current value of all future cash flows generated by the project, including the initial capital investment. The NPV method is widely used in budgeting to establish the most optimal project (with the greatest possible profit). The formula for NPV method varies depending on the numbers and consistencies of the future cash flows. Also, the discount rate and assumed period of the analysis is meaningful. The NPV can be generally defined with the following equation.

$$NPV = \sum_{t=1}^{n} \left(\frac{cash\ flow(t)}{(1+i)^t} \right) - initial\ investment \tag{2.2}$$

If analysing the specific, longer-term project, formula (2.2) can be rewritten as follows:

$$NPV = \sum_{t=1}^{n} \left(\frac{1}{(1+R_d)^t} \cdot \Delta O_U \right) - N_U \tag{2.3}$$

It is very easy to evaluate the results obtained from the NPV analysis. If the obtained value of NPV is greater than 0, then the investment is profitable. Whenever the NPV is equal to 0, this means that the savings are equal to the project costs. When the NPV is negative then the investment is unprofitable. The NPV method is more exact and reliable comparing with the SPBT but still not as comprehensive as the LCC analysis.

Nevertheless, the NPV method is much more popular in several countries (including Poland) than the LCC method. The NPV method is successfully used in the industry, as well as academic researches [187], [247].

According to the **E**nergy **P**erformance of the **B**uilding's **D**irective (EPBD) [335], retrofits should target the cost-optimal solutions [177]. The LCC method is recommended to be applied during the planning phase for renovations in order to select the cost-optimal solutions [141], [183]. The LCC method is the most accurate and most reliable method for the economic assessment of a project. The method considers all the important expenses throughout the building lifetime. The optimal design minimizes the sum of operation (energy used for the indoor space conditioning) and construction expenses over the building lifetime [21]. Sometimes, the LCC method is compared to the floating iceberg (see **Figure 2.32**) – above the surface, we can see only a small part of the whole (initial costs), while the rest of it is not visible, under the surface (most of the cost are hidden or unnoticeable during the investment). The initial costs typically constitute only approx. 15 % of the total cost of the building project during its whole lifespan. The LCC analysis includes the construction expenses, which are the initial costs, and the future costs, related to the operation, maintenance, service, repair, potential replacements expense, as well as the residual values (*e.g.* energy usage).

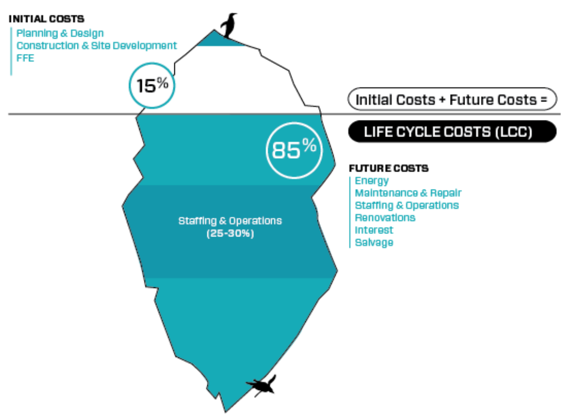


Figure 2.32. *LCC method basis illustrated with the iceberg principle (source: [342])*

In general, the LCC can be defined as the sum of all cost that occurred during the time of the lifetime of the proposed modernization. It can be expressed with a basic equation in the form (2.4). Although, the LCC value requires consideration of the energy pricing as well as the inflation rate. According to [347], the LCC analysis is considered as the global cost estimation and can be calculated using the equation (2.5).

$$LCC = C_{initial} + C_{operation} + C_{repair} + C_{replacement} \tag{2.4}$$

$$C_G(\tau) = C_I + \sum_j \left[\sum_{k=1}^{\tau} \left(C_{O,k}(j) \cdot R_{DR}(k) \right) - V_{f,\tau}(j) \right] \tag{2.5}$$

2.5.2. ECOLOGICAL ASSESSMENT METHODS

Presently, there are numerous of methods to rate the building sustainability. The concept of the SD started to be seriously considered in the early 1990s and since the beginning, it received a rapid interest in most scientific and industrial domains. The SD basis, which is focused on an equilibrium between the environmental, economic and social aspects, fits perfectly within the framework of cities. Thus, **S**ustainable **U**rban **D**evelopment (SUD) is becoming more and more popular in order to achieve the urban scale sustainability [98].

The number of different building rating systems are set to rise in the nearest future [169]. Each region has the most popular method for the multi-criteria building assessment [218] (see **Figure 2.33**). Nevertheless, all the methods used for buildings sustainable assessments have the same goal – to rate the analysed building in terms of its impact on the natural environment. Sustainable building certifications effectively support the integrated design and interdisciplinary collaborations, as well as develop energy-efficiency and sustainability in the building sector. To receive a high mark, the analysed structure needs to be designed appropriately, using the novel technologies and materials, being environmental-friendly as well. The buildings with sustainability certificate outperform conventional buildings in terms of the environmental, economic and social parameters.

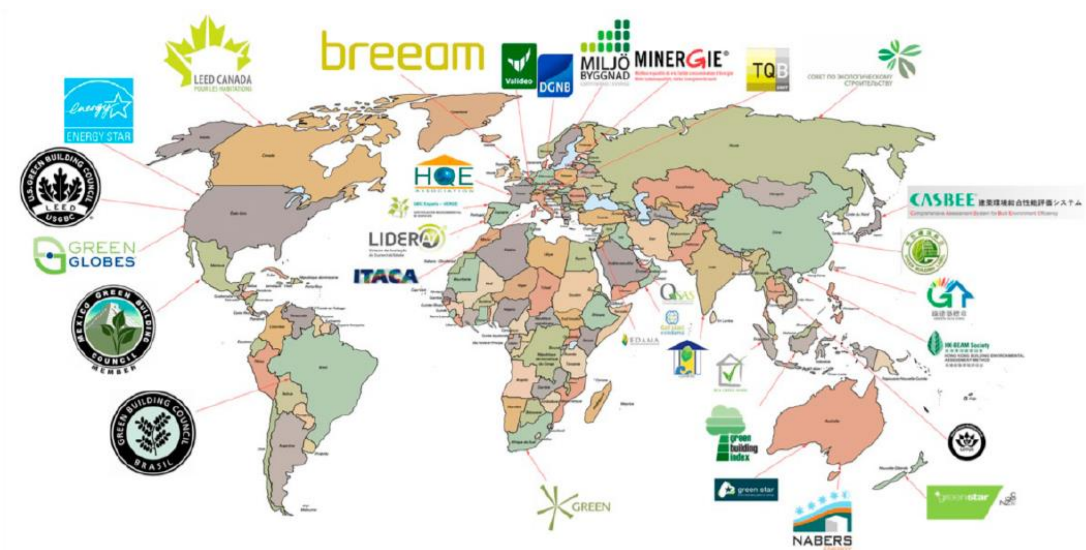
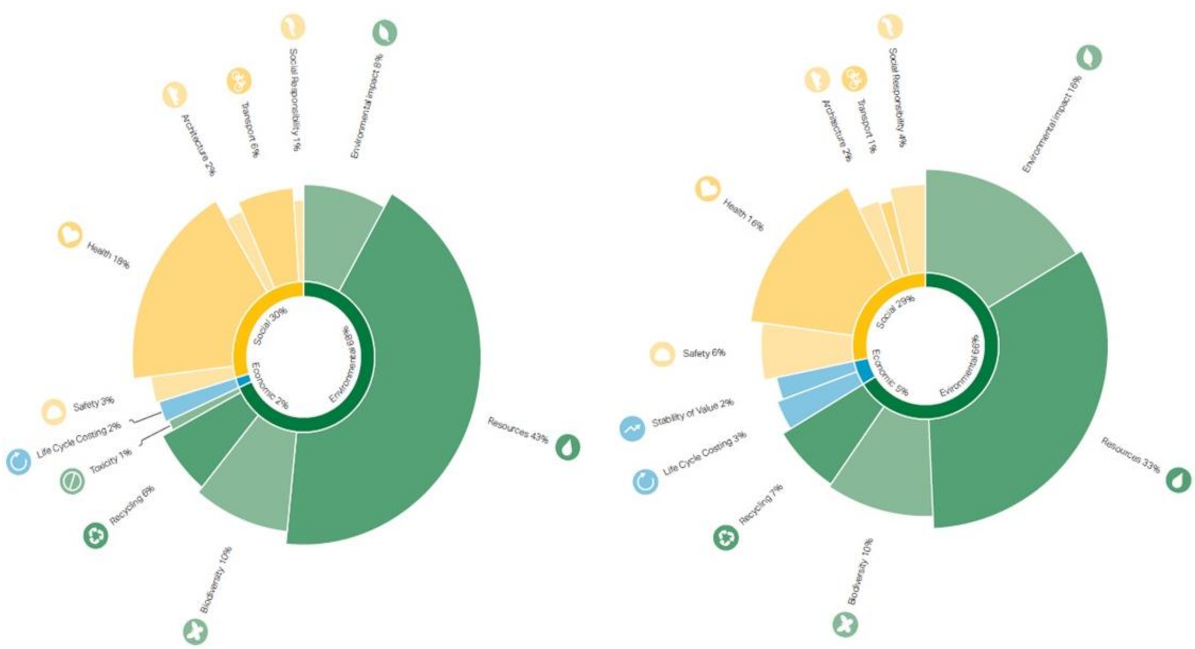


Figure 2.33. World map of multi-criteria methods for buildings assessments (source: [218])

There are two key types of building rating tools, accordingly the **D**esign-**B**ased **R**ating **T**ools (DBRT) and **P**erformance **R**ating **T**ools (PRT). The DBRT assess the environmental impact, based on the design characteristics of the analysed building (valid for both, the new and retrofitted ones). Some exemplary DBRT are the following, Green Star [385], **L**eadership in **E**nergy and **E**nvironmental **D**esign (LEED) [427] or **B**uilding **R**esearch **E**stablishment **E**nvironmental **A**ssessment **M**ethod (BREEAM) [367]. The PRT evaluate the actual functioning of the building during its operation; an exemplary PRT is the **N**ational **A**ustralian **B**uilt **E**nvironmental **R**ating **S**ystem (NABERS). Typically, each of the building rating tools assess the analysed object in terms of the three pillars of the SD paradigm, using numerous parameters for the final evaluation. Each rating system has different weighting coefficients of each pillar importance, where the German Sustainable Building Council (in German: ***D**eutsche **G**esellschaft für **N**achhaltiges **B**auen,* DGNB) method [373] is characterized with the best balance between weights for the economic, environmental and social aspects. The comprehensive comparison of numerous **S**ustainable **R**ating **T**ools (SRT) can be found in [163], [218]. According to the actual literature review concerning SRT, it can be concluded, that the BREEAM, LEED and DGNB certificate systems are the most popular ones [98]. The interesting fact is that the required minimal score '*to pass*' as well as the difficulty of obtaining the highest mark in each of the certification method is different – a short comparison of the BREEAM, LEED and DGNB systems is presented in **Table 2.5**, while the more detailed one can be found in **Figure 2.34**.



(A) (B)

(**c**)

Figure 2.34. *Detailed comparison of LEED (A), BREEAM (B) and DGNB (C) certificate rating systems (source: [288])*

Table 2.5. *Basic comparison of LEED, BREEAM and DGNB certificate rating systems (source: [288])*

	LEED	**BREEAM**	**DGNB**
FOUNDING	1998, USA	1990, UK	2007, GER
SCORE TO PASS [%]	> 40	> 25	> 50
SCORE TO HIGHEST MARK [%]	> 80	> 85	> 80
ENVIRONMENTAL PILLAR SHARE [%]	68	66	33
ECONOMIC PILLAR SHARE [%]	2	5	30
SOCIAL PILLAR SHARE [%]	30	29	37

Each of the introduced method focused on another combinations of the aspects regarding the building lifespan. The primary goal of the above-mentioned rating systems is to examine the analysed buildings according to the LCA or CE paradigms – building performance in terms of sustainability is performed using the multi-criteria certification systems [286]. The LCA method is always performed in accordance with the conceptual schema presented in **Figure 2.35**. The LCA method is a tool, which is commonly named as analysis '*from cradle to grave*'. The performed examination assesses various aspects related to the whole product's life, starting from the raw materials acquirement, their processing and manufacturing, followed by their use and finally their disposal. According to [329], the LCA analysis divides the life cycle of the building into several stages (see **Figure 2.36**), accordingly the product (A1-A3), construction process (A4-A5), use (B1-B7), end of life (C1-C4) and beyond the building life cycle (D). Based on the literature overview of LCA application for the buildings [41], [50], [98], [113], [235] it is concluded, that the operation stage (B-phase) is responsible for approx. 80-85% of the total energy used during buildings lifespan.

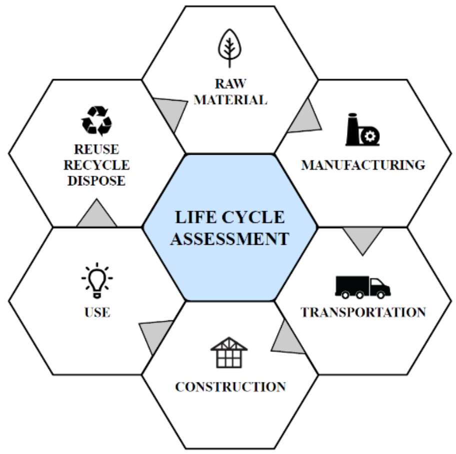


Figure 2.35. *Life Cycle Assessment conceptual schema (own study)*

The comprehensive description of the LCA method (how to perform the assessment as well as to present and interpret the obtained results) is presented in the numerous of standards, accordingly:

- ISO 14040 [352] – principles and framework of the LCA,
- ISO 14042 [353] – impact assessment outlines,
- ISO 14043 [354] – life cycle interpretation (results),
- ISO 14044 [355] – list of requirements and guidelines,
- ISO 14047 [356] – exemplary assessments,
- ISO 14048 [357] – documentation format information.

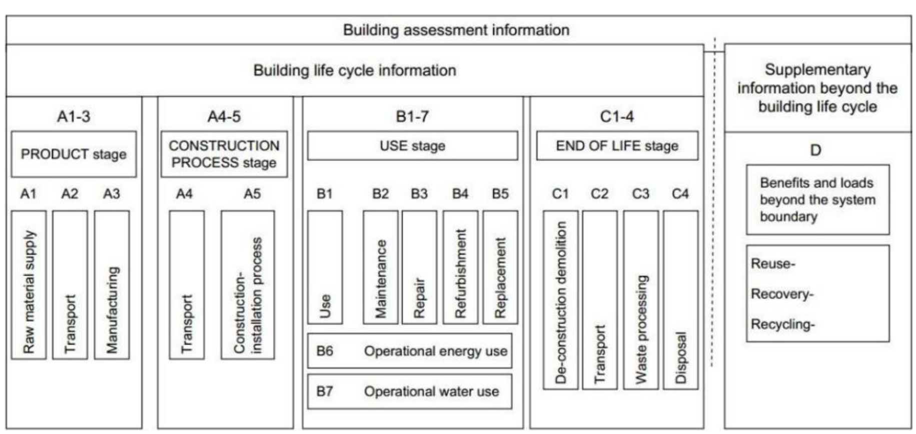


Figure 2.36. *Building assessment modules for LCA (source: [329])*

CONCLUDING REMARKS

Summarizing, it is difficult to accurately predict the lifespan of a building – buildings are durable and all the decisions affecting them have long-term consequences. Thus, all buildings should be analysed before the construction to optimize the long-term economic and environmental profits. The same practice should be applied to the existing buildings, which require some modernizations or refurbishments. It is required to choose a proper period of assessment in order to obtain the valid results of the economic or environmental analyses. After all, the economically optimal building design minimizes the sum of construction and operating expenses (energy costs accrued from space conditioning) over the building lifetime.

The economic assessments can be performed using various methods. Some of them are rather simple (*e.g.* SPBT), giving only an only cursory overview of the analysed project profitability, while more comprehensive ones (*e.g.* NPV, LCC) are capable to perform more accurate examinations. The LCC method makes it possible to find the cost-optimal **E**nergy **E**fficiency **M**easure (EEM) package for a building. The LCC is the most comprehensive type of economic analysis of the project in general (which might be both the building operation phase as well as its refurbishment). Using the LCC method we obtain the reliable financial assessment of the analysed project – this is a good solution towards profitable invests within the building sector, which will simultaneously improve energy-efficiency of the specific buildings and whole the cities.

The environmental assessment, usually performed using the LCA method allows designing a sustainable urban environment, using the energy-efficient and environment-friendly buildings. For buildings the operation phase is the crucial one in terms of sustainability, nevertheless, other stages cannot be neglected. It seems like the LCA-type of analyses will become a required standard in the nearest future.

Nowadays, there are numerous computer softwares, which allow us to perform various complex economic and environmental analyses. The availability of information and the usage of computational technology allows us to perform the comprehensive simulations and analyses which help in limiting the environmental hazards. Additionally, numerous multi-criterial rating systems (buildings certificates) are a helpful tool towards urban sustainability. It is of our interest to select the most efficient solution for both, the economic and environmental aspects. Unfortunately, usually the most economically profitable solution is not equally beneficial environmentally – therefore it is essential to select the variant, which is optimal for the both aspects. An exemplary study in accordance with the SD paradigm for building applications was performed by the author and published in [284].

2.6. ENERGY CLUSTERS – THE FUTURE OF ENERGY EFFICIENCY

Energy Cluster is a new concept on an energy efficiency roadmap. The major motivation to define an EC concept was a national energy safety (independency of environmental phenomena or power plants breakdowns). The EC become more and more popular every day, globally. Whenever locally performed action results in energy efficiency improvement, an EC can be established. It is necessary to mention, that there is still no official regulations on ECs. Nevertheless, governments of Poland and other highly-developed countries are unceasingly working on legal regulations regarding ECs. In Poland, the Energy Cluster was defined for the first time in 2016 [342]. According to [342]: '*Energy Cluster is a civil-law agreement, which may include natural persons, legal entities, scientific and research institutes or local government units, concerning grid load management, energy production & distribution, as well as, a local energy market of Renewable Energy Sources or conventional fuels, located on the operated area of the analysed cluster*'. Energy specialists and experts are consistent with statement, that ECs are a new beginning of highly energy-efficient areas. Recently (since mid-2019) an EC concept began to be replaced with the phrase *'Energy Cooperative'* in Polish nomenclature.

Polish government (particularly Polish Ministry of Energy [303]) and some associate organizations [391], [414], [415] are intensively working on national norm referring to the EC concept. Also, the main energy operators of Poland are strongly interested in ECs development. In late 2016, a comprehensive report about the functionality of ECs in Poland was published [303]. The main goals fulfilling by ECs are as follows:

- energy safety (accomplished mainly from local productions),
- increasing the installed capacity of the national energy system,
- independence from foreign fuel supplies,
- development of dispersed energy production,
- increasing shares of RES usage,
- grid reliability improvement,
- improvement and rationalization of local resources usage (maximizing a local potential),
- utilization of harmful wastes and water-conserving as well as air quality improvement,
- low-emission public transportation and e-mobility development.

Regarding the published documents and reports about operations toward the energy efficiency improvement and stability of the analysed region, the temporary definition of an EC was defined. An EC creates conditions of stable, sustainable (society, environment, economy), modern (innovation) and effective (technology, energy, business) growth of the dispersed energy, including RES application, resulting in improvement of local energy safety as well as provides economic competitiveness with the usage of regional resources. The potential application of an EC can be grouped into 5 main fields, which can be implemented together or separately (see **Figure 2.37**).

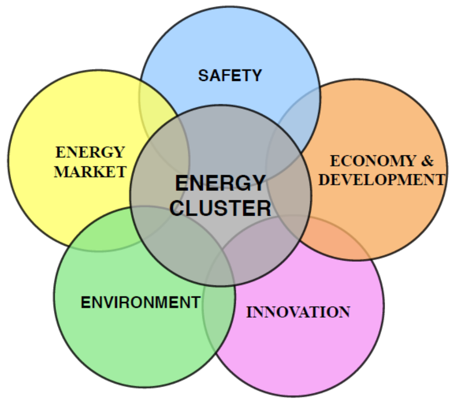


Figure 2.37. *Energy Cluster fields – concept (own study, based on [414])*

Nowadays, ECs are focused on natural resources usage (mostly renewables and local resources) with flexible load, consumption and grid management of the analysed area. The detailed schema of operations agreeable with an EC concept can be seen in **Figure 2.40**.

From the author's point of view, all of the actions resulting in energy efficiency and grid safety improvements of the analysed area might be considered as a basis to establish an EC. An EC definition is very widely understood – it can be considered as an energy-related service for potential consumers. In **Figure 2.38** we can see possible service types following the EC concept.

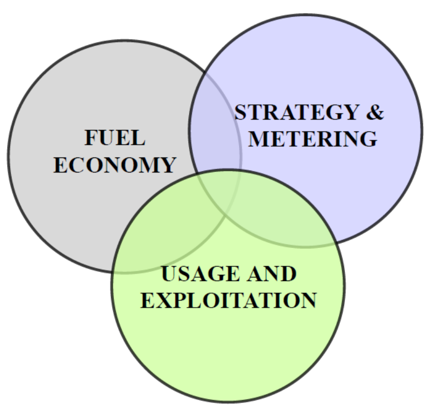


Figure 2.38*. Possible service types of Energy Cluster – concept (own study)*

It is complicated to define all possible actions which fit within the EC concept, due to its comprehensive definition. According to [414], we might assume 125 possible activities of an established EC (see **Figure 2.42**). Those activities are divided into 3 main groups of possible fields of services – each section can be characterized by 5 different features. The conceptual graph was presented as a cube (5x5x5), in which we can adjust an analysed activity – *e.g.*, considering electricity usage, we weigh up electricity (from *fuel economy* group), exploitation (from *usage and exploitation* group) and consumption (from *strategy & metering* group).

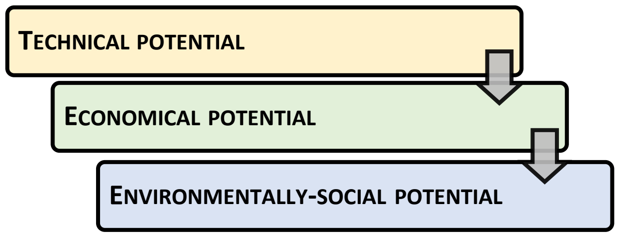


Figure 2.39. *Schema of EC potential analysis (own study, based on [303])*

It is important to evaluate the potential of an analysed EC by means of local energy production assessment. According to [303], the potential of an EC is examined in 3 steps: technical, economical and environmentally-social fields. The assessment process is strictly defined – each group is examined in a determined order, based on recursive technique (see **Figure 2.39**).

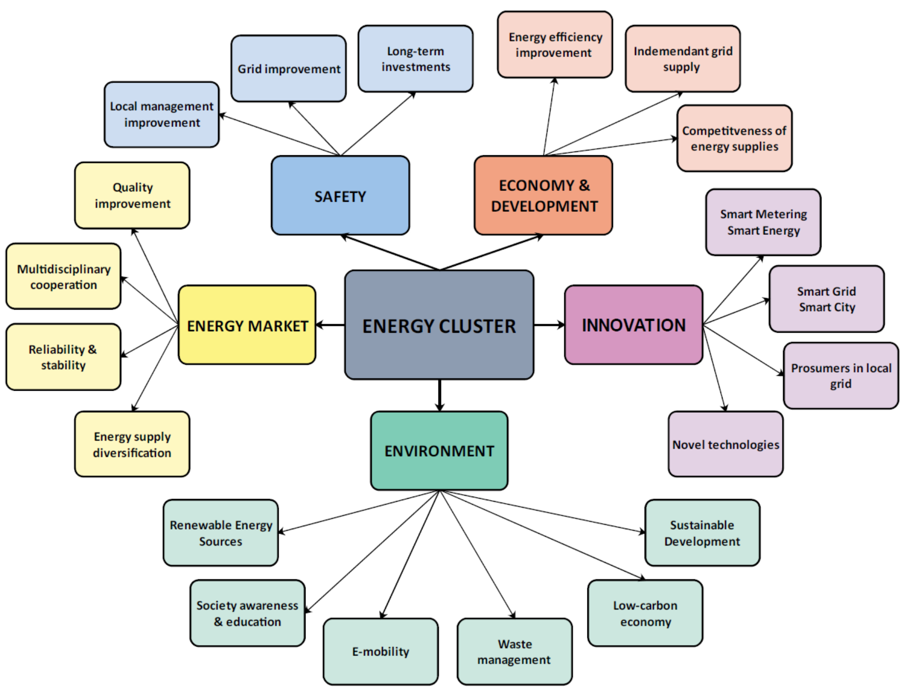


Figure 2.40. *Detailed schema of possible actions compatible with an EC concept (own study, based on [414])*

Furthermore, all performed within an EC are acquiescent with the Sustainable Development principles. Based on a graphical concept of the SD paradigm (see more in section **2.5**), an adequate graph for ECs was obtained (see **Figure 2.41**). A social aspect is substituted with safety conditions, environmental with local resources usage and economic with potential competitiveness. A common part of all 3 fields is a basis to establish a stable, energy and environmental efficient EC.

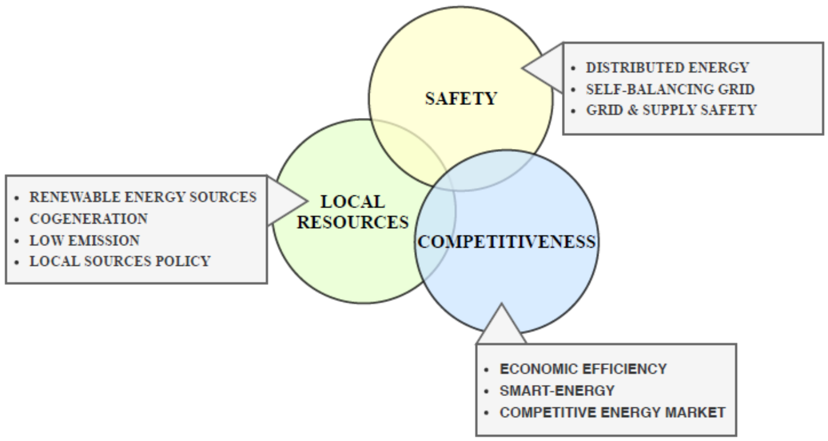


Figure 2.41. *A concept of Energy Cluster schema based on Sustainable Development principle (own study)*

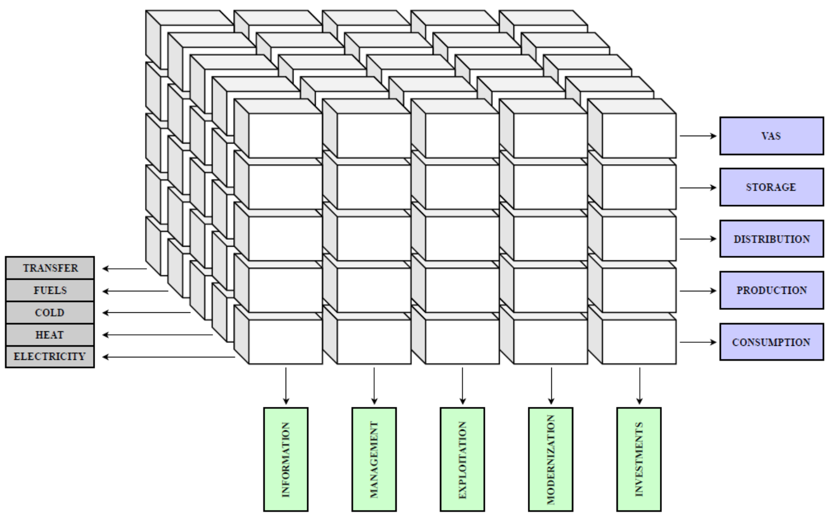


Figure 2.42. *Possible activities of Energy Cluster - concept (own study, based on [414])*

Poland seems to be one of a leading country in ECs development and implementation [189], with a strong emphasis on pilot clusters promotion. The Ministry of Energy of Poland already announced a competition for a *Pilot Energy Cluster Certificate* twice, in 2017 and 2018 [390]. Results were announced accordingly in May and November of 2018. Presently, Poland has 66 representatives ECs (selected through 199 applications), located within the whole territory of Poland. Clusters are located in 15 provinces of Poland (see **Figure 2.43**), with the largest amount of 10 in *Mazowieckie* region [390]. Each of the *Pilot Cluster* (PC*)* is focused on various aspects providing energy efficiency improvement. One of the main purposes of PCs initiative was to gather information necessary for further work on legal regulations and guidelines result in the development of energy-efficient areas. The award for the best Polish cluster was granted to the project named *'Czortynski Energy Cluster'* [243], [371]. Keynote and aim of the leading cluster are based on usage of the natural environment for energy production purposes (hydro-power plant).

Out of all energy-efficient strategies, smart grid areas seem to be the most adequate with an EC concept. Both approaches of a local grid improvement have lots in common and might be used interchangeably.

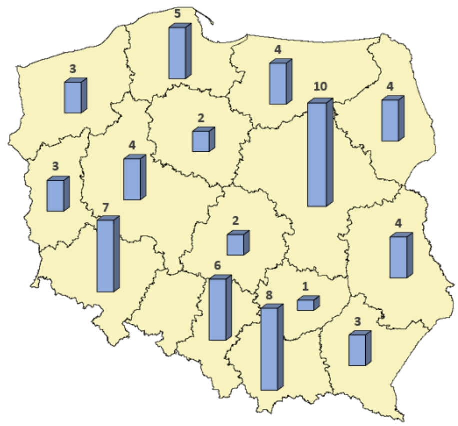


Figure 2.43. *Distribution of Polish PCs – sorted by provinces (own study, based on [390])*

ECs have a huge potential to become a driving force of changes within the national energy system, especially with fields focused on novel technologies of energy efficiency improvement, notably smart grid, smart metering, energy storages, RES usage and e-mobility. Summarizing, based on performed overview, the main goals of EC are defined, as follows:

- self-balanced, energy-independent areas,
- energy grid stabilization, safety and reliability improvement,
- development of RES usage,
- low-emissions policy support,
- Sustainable Development implementation,
- modernization & development of rural areas and communes,
- energy, financial and environmental profitability,
- innovation – cooperation with scientific and research institutions,
- increased awareness of local society about energy production & consumption.

CONCLUDING REMARKS

The emergence of smart grids, energy advanced buildings, RES applications, as well as increasingly applied energy management technologies improve energy flexibility and efficiency of urban areas. Those energy flexible urban areas improve distributed energy systems development, which is necessary for the inevitable transformation of a traditional grid.

Whenever the group of buildings is considered, performed analyses are following EC concept – a novel approach of energy-related studies. In general, all actions resulting in energy-efficiency improvement, on a defined area, might be a basis to establish an EC. Thus, whenever a group of buildings is considered, it is possible to study them as unity, constituting **B**uilding **E**nergy **C**luster (BEC). Depending on applied techniques of energy-efficiency improvement, a standard BEC might become an EFBC – the most advanced model of EC concept. EFBC concept is an excellent approach for improvement in UEM for neighbourhoods concerning energy, economic and environmental aspects. UEM is still an innovative approach of city-scale energy modelling, where better energy planning and operation controls are required. Therefore, it is recommended to apply the EFBC concept as a standard for new, as well as renovated residential neighbourhoods. The above-introduced approach is extremely important in order to improve the energy standard of the Polish residential sector.

Presently, available computational tools are focusing on single buildings approaches, while for urban-scale modelling all buildings constituting the analysed areas should be considered simultaneously. Therefore, the necessity for a valid tool, for residential EC analyses is superior. The performed dissertation is based on BEC approach for Polish households, performed by means of developed computer tool – *TEAC*. Numerous exemplary residential areas were examined and presented in the content, in terms of energy, economic and environmental analyses. EC approach (or more precisely BEC) is an excellent method, working out for Polish residential sector analyses.

2.7. *ENERGY PLUS* – SOFTWARE USED FOR BUILDINGS ENERGY-RELATED ANALYSES

Presently, computer simulations are regularly used for solving various problems, becoming one of the most important analytic tools. Using advanced simulations it is possible to predict an outcome or forecast specific phenomena in many fields. The importance of simulations is invaluable for buildings analyses – they are successfully applied for planning, design and construction purposes. Moreover, simulations are a helpful tool for buildings energy-related analyses. The indisputable value of computer simulations is a possibility to evaluate some alternative solutions before applying them in reality. Thanks to that, it is possible to choose the most appropriate solution for the analysed case – usually, using computer simulations is highly financially rewarding.

For the past several decades, computer softwares are used by architects and engineers. For civil engineering, the dissemination of computer tools was a breakthrough for a design process. Since buildings design is a complex process, simulations are extremely helpful for designers. Computational simulations might be used to support the decision making for individual buildings, as well as whole residential neighbourhoods. Buildings-related simulations are usually performed in order to analyse their durability or usage costs. During the building design process, computer simulations help evaluate numerous building enclosure solutions, as well as to select the appropriate HVAC system. Selected solutions should provide a durable structure simultaneously with energy-efficiency followed by ensuring appropriate interior climate conditions. Additionally, it is required to define operations occurring in the analysed building, related to occupants as well as equipment. Unfortunately, it is difficult to predict all possible operations within the analysed building at the design stage, because of irregular residents behaviours or variability of the exterior climate conditions. Thus, it is also crucial to perform building simulations during buildings' existence in order to optimize energy consumption and operating costs or to make a decision of refurbishment.

Presently, there are numerous softwares, which are capable to perform comprehensive energy-related analyses of a single building. These computational models can examine numerous phenomena occurring in the analysed building simultaneously in order to estimate its' performance. Moreover, computer simulations are a proven method used for various buildings analyses. The building definition process is based on a set of input data, describing the analysed object. Additionally, exterior and interior conditions need to be defined. Based on a complete set of data, advanced computer softwares can calculate an energy profile of the examined building. The major factors which affect the energy profile of the analysed building are its enclosure parameters, weather conditions (especially exterior temperature and solar radiation), interior environment management as well as active systems efficiency. After finishing building definition process software can perform simulation in order to obtain results. The calculation time is highly dependent on the complexity of the analysed building, as well as requested outputs. Nevertheless, building simulation tools are key for evaluating essential issues referring to buildings' performance.

The **B**uilding **E**nergy **M**odelling **P**rograms (BEMPs) became popular since the late 1960s [3]. BEMPs have been developed to perform a wide range of buildings energy-related analyses. The number of that type of computational tools is still rising and they are widely in use by engineers and scientists. Due to the huge assortment of BEMPs, it is crucial to define the main purpose of the planned examination in order to select an appropriate software. Most of them are capable to perform a comprehensive analysis of a whole building, nevertheless, if only one factor is under consideration (*e.g.* daylighting) it is recommended to select a specialized tool (recommended for those type of examinations).

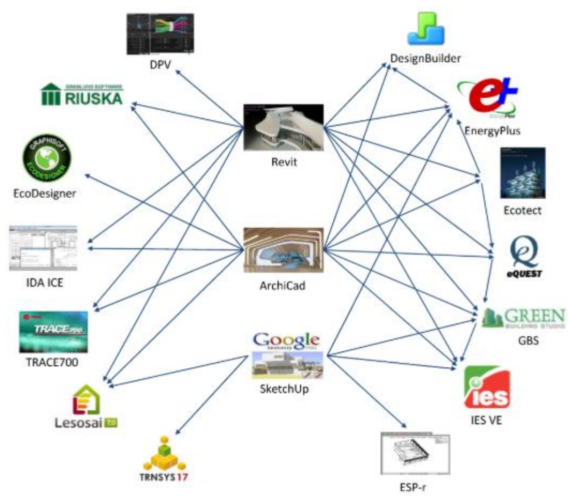


Figure 2.44*. Links and connections between today's BEMPs (source: [35])*

Presently, the most comprehensive and universal simulation software for building energy-related analyses is *Energy Plus* [378]. The *Energy Plus* software was used in this dissertation in order to define the analysed buildings. It is a next-generation BEMP [59], funded by the U.S. Department of Energy [425] since 1996. The *Energy Plus* software successfully substitutes previous BEMPs, accordingly *DOE-2* [374] and *ESP-r* [380] (nevertheless, these programmes are still in use), while its' biggest competition is *TRNSYS* software [424]. All of the above-mentioned BEMPs have a common factor – all of them are calculation models, performing comprehensive buildings simulations, made based on input parameters defined by the user. It is important to use an authorized input data due to the fact, that the *Energy Plus* software is only verifying the acceptability of a range of various parameters. Also, the *Energy Plus* (as well as most of the BEMPs) is not assisting the user during the building definition process – it is rather not a user-friendly tool. The dependencies between various BEMPs can be seen in **Figure 2.44**. Due to the fact, that the *Energy Plus* software was used in the performed analyses it will be described in detail.

The *Energy Plus* software is used by engineers, architects and researches to define whole buildings and perform simulations for various purposes. It is based on a combination of algorithms used in *BLAST* and *DOE-2* softwares, with modular, structure code. It is basically a calculation model, using text files as inputs and outputs [325], [326]. Since the beginning, the *Energy Plus* has numerous features and enhancements, supporting buildings design and operation control. The *Energy Plus* allows simulating buildings in order to model both energy consumption and water use. As a result, heating and cooling loads are calculated, but also electrical system responses (*e.g.* lighting or domestic equipment). The software provides more accurate, realistic results due to the complexity of input parameters. Thanks to detailed HVAC system definition, it is possible to provide more accurate behaviour of analysed spaces, as well as it helps with better installation design of the analysed building. There are several comprehensive graphical interfaces for the *Energy Plus*, simplifying the process of analysed building geometry definition. The data stream within and around the *Energy Plus* engine can be seen in **Figure 2.45** – it is also a visualization of the calculation process.

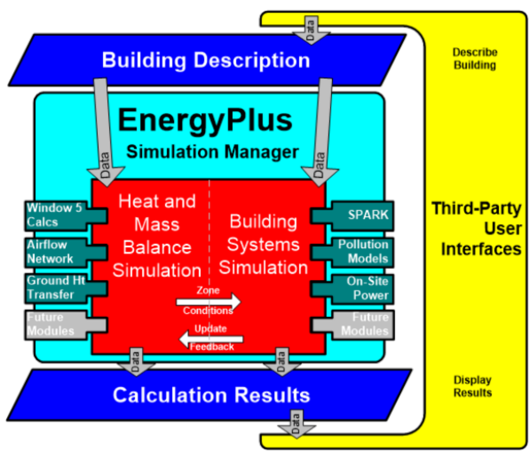


Figure 2.45. *The Energy Plus structure – the general picture (source: [324])*

The *Energy Plus* is a universal simulation engine, which might be modified by the user according to individual needs. Below, the main features and applicability of the *Energy Plus* software are presented, according to [323], [324]:

- ***an integrated, simultaneous solution*** where the building response is analysed with tight coupling of the primary and secondary systems,

- ***sub-hourly, user-definable time steps*** for the interaction between the thermal zones and the exterior environment, also allowing to perform simulations with appropriate time step depending on analysed phenomena,
- ***heat balance-based solution*** technique used for radiant and convective effects calculation at both interior and exterior surfaces (building thermal loads),
- ***transient heat conduction technique*** using a conduction transfer function applied for elements such as walls, roofs or floors,
- ***improved ground heat transfer modelling*** allowing usage of three-dimensional finite-difference ground models or simplified methods,
- ***combined heat and mass transfer,*** in other words, an effective moisture penetration depth model (including adsorption and desorption),
- ***thermal comfort models*** based on standard parameters like activity, indoor **d**ry-**b**ulb **t**emperature (DBT), humidity, air velocity, *etc.*,
- ***anisotropic sky model*** technique for advanced calculations of diffused solar,
- ***advanced fenestration calculations*** including the impact of blinds or electrochromic glazing but also layer-by-layer heat balances for proper calculation of solar energy absorbed by windows panels,
- ***daylighting controls*** including interior illuminance calculation as well as the effect of reduced artificial lighting on heating and cooling,
- ***loop-based configurable HVAC systems*** allowing to model typical building systems,
- ***atmospheric pollution calculations*** predicting CO_2, CO, SO_x, NO_x emissions,
- ***links to other popular simulation environments/components*** to allow a more detailed analysis of buildings components.

Based on the above points it can be concluded, that the *Energy Plus* software is a powerful and universal computational tool for whole-building analyses. In **Figure 2.46** the structure of the *Energy Plus* integrated solution manager was shown. It is an interface between three main calculation modules: surface heat balance manager, air heat balance manager and buildings systems simulation manager. The surface heat balance module is mainly responsible for interconnections with boundary conditions, surface heat balance, conduction, convection, radiation and mass transfer effects. The air heat balance manager calculates various mass streams, including air movements, ventilation and infiltration. Finally, the building systems simulation manager controls the HVAC and electrical systems calculations.

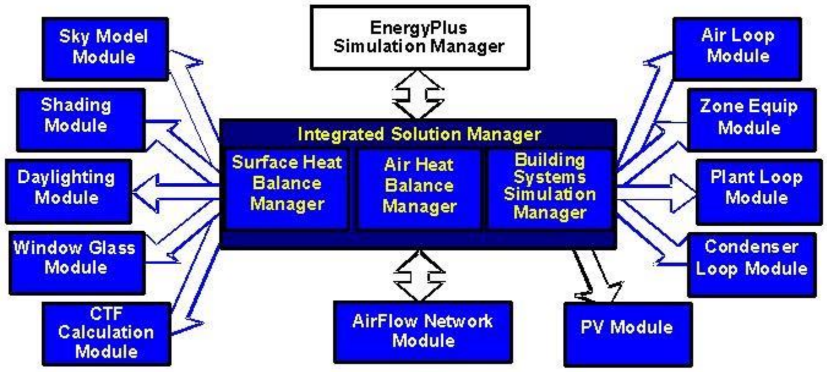


Figure 2.46. *The Energy Plus software schematic (source: [323])*

The testing and validation studies of obtained results by the usage of the *Energy Plus* software are widely available for a dozen years [102], [267], [268]. There is no perfect software, which can handle all kinds of assessments. However, the *Energy Plus* is capable to handle the majority of buildings and HVAC design options to calculate energy consumption for a defined period of time. More information, details and examples can be found in the comprehensive documentation [323], [324], [325], [326].

The *Energy Plus* software is the major tool used by the author of the dissertation. Numerous studies have been performed for various building types as well as considered scenarios. In [279] the investigation of a DSM techniques for a group of commercial buildings were performed. Using simulations performed by means of the *Energy Plus* software it was proved, that proper management of public buildings (accordingly office building, movie theatre, hotel and large-area mall) might result in more stable and homogeneous demand in the local grid, with lower peak loads. In [280] an analysis of energy efficiency and thermal comfort for an office building complex was performed. The study was focused on the assessment of various modernizations in terms of potential profitability. The performed examinations were validated using actual energy consumption data for the analysed buildings. All proposed modernizations were tested using energy-related simulations performed by means of the *Energy Plus* software. Obtained results confirm potential energy and economic improvements for the analysed building complex simultaneously keeping occupants thermal comfort at a satisfactory level. In [283] an analysis of wind energy application for electrical energy supply to a residential area was performed. The analysed neighbourhood consists of three different types of single-family houses (defined using the *Energy Plus* software), fully supplied with electricity. Wind energy potential was investigated for onshore and offshore scenarios. As a result, the analyses of a local electricity grid were performed, through LDC. In recent articles [281], [282] the presented results were focused on the presentation of a home-developed the *TEAC* software (see more in section **3.7**) for Polish residential sector analyses. The *TEAC* software is based on parametric simulations performed by means of *Energy Plus*. As a result, energy and environmental assessments were obtained for the analysed residential areas.

Unfortunately, each of the BEMPs has its own calculation methods, resulting in large discrepancies between the simulation outputs obtained by each tool. Even for the same building, defined by the same person, we might observe significant differences during the analyses – comparison between different BEMPs is a popular research area [58], [277], [278]. A detailed comparison between different BEMPs, according to the information provided by the developers, is presented in [58]. A list of most of the softwares used for buildings energy-related analyses, with a brief description, can be found at the *BEST Directory* website [369]. Nowadays, BEMPs can be integrated with numerous different softwares used for various analyses within civil engineering fields (see **Figure 2.44**). Some of these programmes were developed in order to ease a building definition process in models like the *Energy Plus*. The mentioned programmes might be considered as an overlay softwares – all-important calculations are performed using models such as the *Energy Plus*. In general, these softwares are user-friendly due to the transparent **G**raphical **U**ser **I**nterface (GUI), used during buildings' definition process (especially their geometry). The most popular ones, used with the *Energy Plus*, are *Design Builder* [372] and *Open Studio* [394]. *Design Builder* is a user-friendly software, used for defining and simulating virtual buildings models. It is easy-to-use simulation software, dedicated for quick assessments of new or existing buildings' performances. It was developed to minimize buildings' definition process time simultaneously maximizing users' productivity. *Design Builder* software was used in the performed study in order to define the analysed building's geometry. The biggest advantage of the *OpenStudio* is its compatibility with the *SketchUp* software [398], which is commonly used along with many architects. *SketchUp* plug-in allowing to view and edit 3D models, used for energy simulations afterwards.

At the end it is necessary to mention, there are numerous specialized programmes, which are capable to analysed whole regions used for UEM [220], [269]. The most popular ones are ***U**rban **E**nergy **I**nterface* (UMI) [392], *CityBES* [403] or *CitySim* [404]. Presently, numerous researches have been performed using those softwares. Unfortunately, the above-mentioned programmes using numerous simplifications, which significantly affecting the credibility of defined buildings' energy profiles. Thus, using the above-mentioned programmes, the complexity of defined buildings constituting the analysed region is unsatisfying comparing with the *Energy Plus* software standard. Therefore, for the purpose of the dissertation, all buildings were defined using the *Energy Plus* software, including the urban area impacts (see more in chapter **3**).

CONCLUDING REMARKS

Computer simulations are presently the best way of predicting buildings' performance before they are constructed or operated. Additionally, computational simulations are the most effective approach to the estimating existing buildings, particularly used in energy, environmental and financial fields. Computational simulations are perfect solutions in terms of assessment of proposed buildings renovations. It is always cheaper and better for the natural environment to perform computer simulation rather than to assemble an inefficient building.

Whenever a computational analysis of a building is considered, the set of input parameters is required, related to geometry, building enclosure as well as facilities and operation. Each of the defined building models should be compared with the actual energy consumption data – only using verified outputs it is possible to perform rational assessments. Also, buildings analyses performed using the *Energy Plus* type of softwares should be executed by an experienced user, who is familiar with the selected tool. Buildings defined by qualified operators will be free of errors or inadequacies, which are typically neglected by inexperienced users.

Summarizing, the *Energy Plus* software might be significant facilitation of the building's design process, nevertheless, it required highly-skilled users with specific knowledge of the analysed study. Engineers and architects will always be a fundamental part of the design process with the usage of the *Energy Plus* software. It is important to remember, that the *Energy Plus* software cannot replace architects or engineers. It requires a valid definition process because there is a risk of receiving not rational results (in accordance with '*garbage in – garbage out'* phrase).

In this dissertation, the *Energy Plus* software was used to obtained buildings' energy profiles outputs. The *Design Builder* software was used during the buildings' geometry definition.

2.8. ARTIFICIAL INTELLIGENCE APPLICATION FOR BUILDING ENERGY ANALYSES – A BRIEF STATE OF THE ART REVIEW

Presently, ANNs are a popular and helpful approach used for classification, clustering, pattern recognition and predictions in many fields. Generally speaking, ANNs are a type of model of **M**achine **L**earning (ML), which is competitive to traditional statistical models. One of the biggest advantages of ANNs is their quickness in data processing, valid for various implementations in research fields. Presently, ANNs are successfully applied as a universal function approximation used in numerical paradigms. They were designed with an ability of self-learning as well as advancement in input-to-output mapping. The above-mentioned features are the answer, why ANNs are frequently and successfully applied for handling comprehensive problems in multiply fields of life. The most applications of ANNs in recent years are monitored in handling problems in agriculture, medicine, education, management, engineering, research and science. It is already proven, that ANNs are able to handle with problems, which are challenging or basically cannot be solved by traditional computational procedures. The uniqueness of AI is mostly used by academics, research and engineering studies.

The human brain can be in fact considered as a highly efficient information-processing machine that performs a variety of complex operations. The unique design of a human brain is its capability to self-intuition information processing, which allows humans to recognize speech or image, process language as well as perform elementary activities such as breathing and eating. Generally, ANNs are imitating the human brain, they can learn by example nevertheless, they perform given the task of interest. ANNs have proved to be a universal approximator – they can be successfully used for solving various multi-variable problems, including optimization.

Whenever research is focused on fields of energy consumption in buildings, numerous variables are involved. For instance, analysing the energy efficiency of a building it is necessary to include numerous variables and parameters, which typically interact with each other, in not fully understood way. Also, buildings performances vary on the exterior climate conditions which are highly unpredictable and variable. Those types of problems are most appropriate for ANNs applications. The application is based on input-output parameters and functional relationships between them. The used data should be based on realistic measurements or estimated using valid tools (such as simulation software). The process of NNs applications can be presented by a three steps approach:

- definition of the problem and network architecture,
- the learning process,
- the testing or diagnostic examinations.

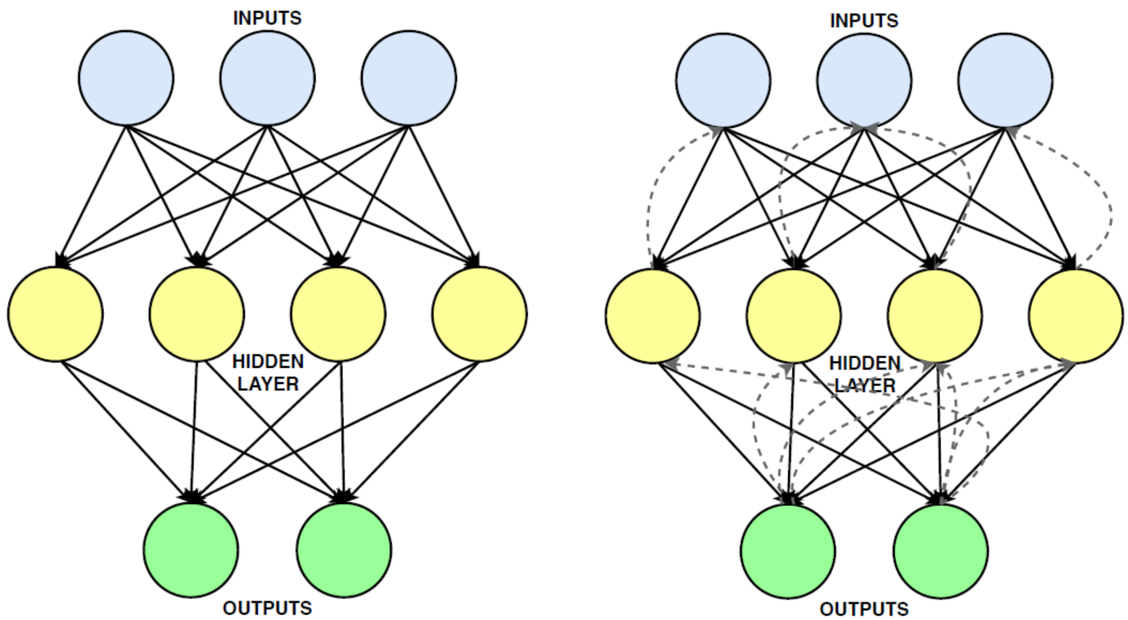


Figure 2.47. *An exemplary schema of FFNN (left) and FBNN (right) structures (own study)*

The ANNs can be classified into two main groups: **F**eed **F**orward **N**eural **N**etwork (FFNN) and **F**eed **B**ackward **N**eural **N**etwork (FBNN). The FFNN is a ML algorithm, based on organized (grouped) layers imitating process accruing in a human brain. In FFNNs signals flow always from input layer to the output layer through all hidden layers – the flow appears between each layer but never within the same one. A singular connection between each unit is characterized by a different weight or strength. The FBNN (sometimes called recurrent networks) can use a type of '*state memory*' to process sequence of data input – those type of ANNs are successfully applied to un-segmentation tasks. In contrast to FFNN in this case some neurons might be feedback – signals can flow in both, forward and backward directions. An exemplary schema of FFNN and FBNN structures can be seen in **Figure 2.47**. The comprehensive classification of ANNs can be seen in **Figure 2.48**.

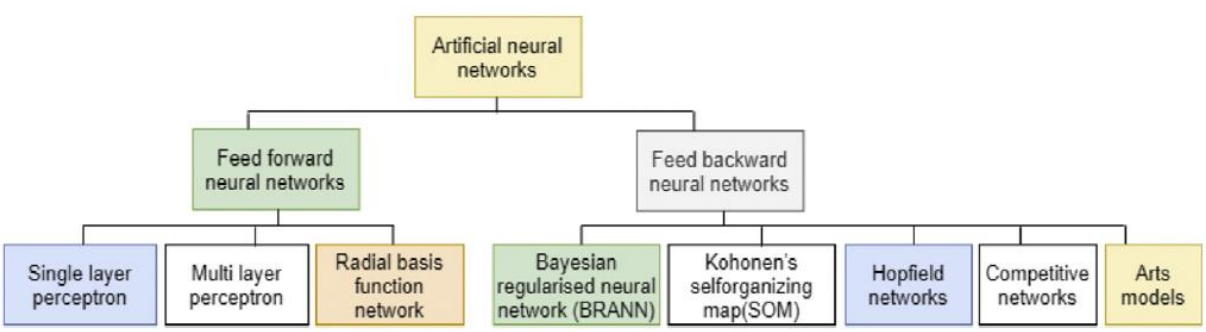


Figure 2.48. *A comprehensive classification of ANNs (source: [15])*

The trained networks are usually evaluated (judged) by means of several types of measures, accordingly **S**um of **S**quare **E**rrors (SSE), multiple correlation coefficient (R^2), **R**oot-**M**ean-**S**quare **E**rror (RMSE) or **C**oefficient of **V**ariation (CV). The obtained value informs, how accurate the defined network is.

Using ANNs it is possible to determine relations in a large quantity of data. NNs are successfully applied as optimization methods, as well as data classification [7], [14], [227]. A complex state-of-the-art overview of ANNs applications can be found in [15], [76]. In [128] a brief overview of ANNs applications for buildings energy-related analyses were performed, including HVAC system variety, solar water heating systems as well as climate conditions. All the mentioned abilities of ANNs fit perfectly patterns of buildings' energy consumption. In the past twenty years, researchers used ANNs in various types of building energy-related analyses, mostly for predictions of heating or cooling loads as well as electricity consumption.

One of the first presentations of NN application for building load forecasting was published in 1991 [207]. NN was applied for electrical load forecast based on measures of past electrical consumptions as well as exterior temperatures. Obtained results were analysed by means of an absolute error – sufficient accuracy was achieved for 24h ahead forecasts.

The hourly forecast of buildings energy consumption continues in [18], [103]. Researchers are experimenting with various network structures in order to obtain be the best accuracy of forecasts. According to the published results, the sufficient accuracy is obtained for networks, where number of hidden neurons is around or lower than number of input neurons.

The energy consumption in buildings is a common topic of investigations, with the usage of ANNs [185]. In [194] an ANN was applied to predict building energy consumption of the University of Sao Paulo building in comparison with results obtained by means of the *Energy Plus* software. It was concluded, that ANNs are suitable for energy consumption forecast, with a sufficient error range of ±13 %. A back-propagation NN was used for the study presented in [54]; the trained network was used for buildings' loads predictions in different climate zones. An hourly energy consumption results obtained from a recurrent NN application for building analysis were presented in [56]. The work was focused on heating and cooling energy predictions for office buildings, based on historical measure data.

ANNs are also successfully applied for residential sector analyses – in [28], buildings' energy estimations were obtained for Canadian households. In the follow-up work [29] the trained network was developed to successfully predict additional consumption within the whole sector, such as energy usage for DHW systems.

CONCLUDING REMARKS

Nowadays, ANNs became more and more popular for various applications in complex scientific and commercial researches. One of the biggest advantages of ANNs is their flexibility and ease of use for many various analyses. ANNs are universal approximators – they have proven to be applicable for solving complex issues including optimization.

Based on the performed introduction as well as state-of-the-art it can be easily concluded, that ANNs are sufficient method used for building energy-related analyses. Their universality was found to be capable of analysing all types of buildings. They are efficient for heating and cooling load predictions, with possible high accuracy, comparing with real data or outputs obtained by computational methods. Application of ANNs might be helpful and time-saving whenever the analysed filed is known – there is a high necessity of appropriate preparation of input and output data. Their application was used in numerous researches and studies in recent years.

For the purpose of the performed dissertation, a NN was used in order to predict heating demand for representative single-family houses of Poland. A FFNN type was selected because they assure sufficient accuracy of load predictions. A single layer perceptron was enough based on selected input and output data usage. Additionally, the defined network was developed to perform heating loads predictions for BCs analyses. The defined NN is capable to predict accurate hourly heating demand based on exterior climate conditions valid for Poland. More information about the network can be found in section **3.6** and subsection **3.7.2**.

3. ANALYSIS DESCRIPTION AND ASSUMPTIONS

The performed analyses aimed to examine the energy profiles and standards of Polish residential building stock in different localizations. Using performed analyses, it is possible to define a trend on how to improve the energy efficiency of the Polish housing sector. A basis of the performed studies is the application of the *TEAC* software – a home-developed computer programme for BEC analyses. Multiple factors, which have an impact on buildings energy consumption, have been investigated as a part of performed work. In this chapter, a detailed overview of the used procedure, performed analyses, made assumptions and developed software are presented.

3.1. APPLIED PROCEDURE

Performed analyses are focused on energy-standard of Polish residential building stocks. Whenever those type of a complex study is performed, numerous assumptions are required (see more in section **3.2**). In this case, we are investigating a residential building stock, thus uncertainties are always part of this type of analyses. Nevertheless, it is an obligation to minimize potential uncertainties to obtain possibly the most valid results.

For the performed studies, an innovative procedure was defined (see **Figure 3.1**), to achieve all expected outlines. The procedure starts with an analysis of the Polish household sector. A group of single-family houses were selected due to their share and impact on the energy demand in Poland. It is possible to perform a similar analysis for another type of buildings (*e.g.* multi-family houses) in the future. The selected single-family houses are considered as representative residential buildings of Poland and their description can be found in section **2.3.2**. Next, all the selected buildings were defined by means of the *Energy Plus* software (see more in section **2.7**). During the process, all predefined assumptions have been used – they are obligate in order to perform a valid *Energy Plus* analysis. Defined buildings models (described in section **3.4**) were considered as the baseline for further analyses. The obtained input files were used in simulations and then validated with the data published in [315] – validation was performed using the only available data: annual final energy consumption for heating and domestic hot water purposes (EK-factor). As a result, the base reference files were obtained. Text-format files, saved as **.idf* (intermediate data format) contain all information about the defined buildings, starting with their positioning, closest surrounding, geometry, buildings enclosures and material parameters, as well as installations schemas and operations schedules. From this point forward, the *TEAC* software application starts. Firstly, the output text files of representative single-family houses of Poland were used for parametric simulations to create a database for further applications. The defined database consists of thousands simulations results performed with hourly calculation step. In total, 358 400 simulations were made. A single simulation took approx. 12 seconds, thus total computing time lasted about 50 days. It is important to mention, that the *TEAC* software database can be freely extended with any additional results. Next step of the *TEAC* software application is related to AI usage. At the beginning, the learning process of the network was necessary (see more in section **3.6**), but since the NN is defined we used it directly, to predict the heating energy demand of buildings constituted an analysed cluster. Obviously, a validation of a trained network was performed by comparing with the results obtained from the *Energy Plus* simulations. It is important to point out, that whenever supplementary results are uploaded into the *TEAC* database, the NN should be re-trained in order to include new outputs – unfortunately, it is possible to obtain much less efficient network (considering its' prediction accuracy) after database extension. The last step is to define a residential area, constituting a BEC. It is necessary to define the analysed area built environment, especially its' shape, size and buildings placements. The definition process of the analysed cluster is performed using the modules of the *TEAC* software (see section **3.7**). In the end, we should define what kind of final results we are interested in – by default the *TEAC* software presents results with usage of maps.

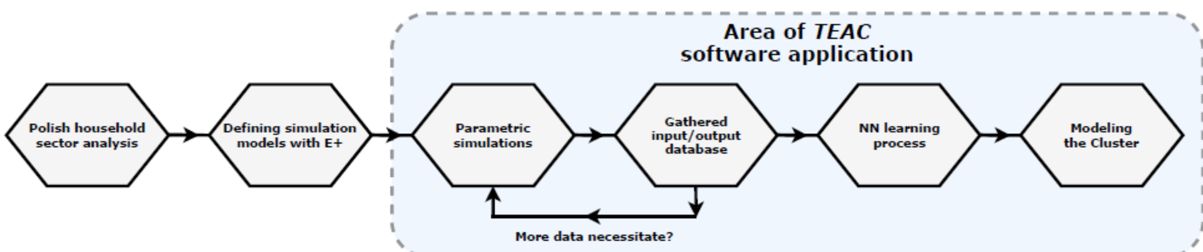


Figure 3.1. *Simple schema of the defined procedure (own study)*

3.2. MAIN ASSUMPTIONS USED IN PERFORMED ANALYSES

During the performed study, various assumptions have been made. Numerous assumptions are caused by the complexity of performed analyses following UEM paradigm. The selection of used postulations is subjective, therefore additional researches on a studied topic are possible in the future, based on other patterns. Each of the below expressed notions are explained in terms of their validity for the performed analysis.

All analyses are performed for Polish localizations. The chosen localizations were selected in order to represent most of the possible climate conditions occurring in Poland. 10 cities were chosen, as it is presented in **Figure 3.2**. A short justification of the performed selection is listed below:

- Gdansk (**1**): a main seaside Polish city, located directly in central-north Poland;
- Leba (**2**): a small seaside city of Poland, located in wind energy advantageous area; a city of Leba is also the closest one to planned Polish offshore wind farm – ‘*Baltica*’ (end of construction estimated before 2030);
- Szczecin (**3**): one of the major cities of Poland, located in the north-west;
- Pila (**4**): selected due to the best wind conditions for Poland (see **Figure 3.4**); a city of Pila is also in close distance with the biggest Polish onshore wind farm – ‘*Margonin*’ – consisting of 60 turbines, with a total capacity of 120MW;
- Wroclaw (**5**): city commonly called as a ‘*hot-island of Poland*’, located in the south-west part of the country;
- Lodz (**6**): city directly in the centre of Poland, the hometown of the author of this dissertation;
- Warsaw (**7**): capital of Poland;
- Bialystok (**8**): a city located in the north-east part of Poland;
- Cracow (**9**): probably the most known Polish city, located directly in central-south of Poland;
- Rzeszow (**10**): a city located in the south-east part of Poland, with good solar radiation conditions as for Poland standards (see **Figure 3.4**).

Each of the analysed localizations is characterized by different exterior climate conditions. The exterior climate of specific location can be defined using a collation of selected weather data, for one-year period. The mentioned weather data can be collated in files, furtherly used for energy-related buildings analyses. Whenever a climate data set is much longer than 10 years’ period of measures it might be used as a characteristic climate for the analysed location. A representative database expressing climate conditions for a whole year duration is known as **T**ypical **M**eteorological **Y**ear (TMY) or **T**est **R**eference **Y**ear (TRY). The comprehensive overview on how to define different types of TMY can be found in [5]. Relevant meteorological files are required by simulation softwares (*e.g. Energy Plus*) to perform reliable analyses. Therefore, for the selected 10 localizations, TMY files were used. Further overview of the used exterior climate conditions was presented in section **3.3**.

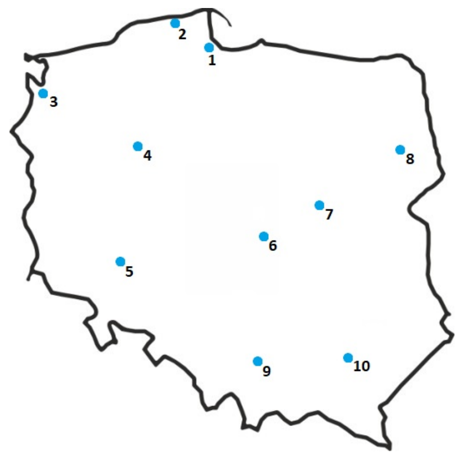


Figure 3.2. *Cities of Poland selected for further analyses in the dissertation (own study)*

The most important assumption relates to keeping focus only on the residential sector of Poland, more particularly on single-family houses. It was motivated by a number of single-family houses in Poland and their actual thermal standard. The share of single-family houses within residential buildings of Poland is overwhelming. Approx. 91 % of housing buildings are single-family type (see more in section **2.3**). Additionally, the energy standard of the single-family houses of Poland is unsatisfying, compering with present trends (see **Figure 2.12**). Additionally, based on the data published by the Central Statistical Office (in Polish: '***G****łówny* ***U****rząd* ***S****tatystyczny',* GUS) [420], approx. 57 % of Polish citizens live in single-family houses. Therefore, it is rational to analyse that type of residential buildings of Poland due to the scale of potential benefits. The data related to residents' attendances, their activity, home equipment and lighting system occupancy rates was assumed in accordance with GUS records (see more in section **3.4**).

Analyses of multi-family houses were abandoned by the Author at an early stage of work because of several major anxieties. Each dwelling is characterized by numerous uncertainties, in most of the cases caused by residents' habits and individual needs. Each multi-family building has at least a dozen dwellings, where each is unique in terms of interior climate conditions or devices working schedules and their energy classes. Each of the mentioned parameters significantly impacts the energy consumption of each flat, as well as the whole building. Additionally, doubts related to the number of residents in each apartment are important – some of the flats might be empty. Furthermore, the study is aimed to analyse and estimate the potential energy savings of residential buildings in Poland, while, in most cases, older multi-family houses have been already thermal-modernized, due to a national trend started in the 1990s. Usually refurbishment of multi-family houses in Poland assumes addition of an insulation layer on exterior walls and roofs. Windows replacement is an individual decision of each resident, so it is extremely difficult to estimate the amount of modernized fenestration in each multi-family house. The mentioned information related to buildings enclosure modernizations and numerous uncertainties related to multi-family houses are a basis to conclude, that energy-related analyses of an archetype for those type of buildings might be unreliable. To perform analyses for multi-family houses sector, numerous additional data (especially related to the energy profile of each dwelling) are required, comparing with data, which is sufficient for a single-family archetype.

Other types of buildings, especially commercial and public ones, were not included in the performed studies. According to up-to-date literature overview, as well as author's knowledge and experience, it is known, that those kind of buildings are unique and they are characterized with much bigger complexity of both construction and installation solutions. In general, each commercial building requires idiosyncratic analysis. The process of building definition is time-consuming, not to mention its' validation phase. To perform an energy demand prediction of a commercial building a very detailed model is required – much more complex comparing with the ones for residential buildings. Including all mentioned above, it is barely possible to perform a universal energy demand prediction method (such as ANN) which could be successfully applied for various commercial buildings. In the end, commercial and public buildings should be investigated standalone – it is the only way to obtain reliable results. Similar conclusions were presented in one of author' articles [280].

Despite the significant potential of an energy-efficiency improvement of historic and traditional buildings, those type of buildings are excluded out of the performed studies. The main reasons are difficulties during potential renovations, performed in a way that prevents from possible damaging of historic fabrics. Those type of buildings always requires a specialist strategy (accepted by conservation officers) during the refurbishment process. Moreover, due to specific construction of a building enclosure, usually moisture-related analyses are required. Historic and traditional buildings should be analysed separately, not as a group within a residential stock.

For all the proposed building refurbishments preliminary thermal comfort analyses were performed. The *Fanger* model was used to validate the interior climate conditions of analysed buildings. The assessment was performed using a time-distribution of a PMV-index, checking the fulfilment of required internal environment conditions. Following parameters regarding the humans' behaviour, accordingly, metabolism and cloths resistance were assumed. Acoustic and visual comforts aspects were not analysed in the dissertation.

Exterior climate conditions were used out of the TMY files for selected Polish localizations. The TMY files are used due to their availability, as well as popularity in those kinds of analyses. Despite the fact, that Polish TMY files are quite out-of-date, their usage is still the best approach to include average, most possible climate conditions for the analysed localizations. Nevertheless, updating the TMY files is necessary in order to perform more accurate studies.

For each of analysed buildings, combinations of proposed thermal-modernizations variants were examined. Proposed modernizations affect building enclosures, as well as their heating systems. Also, for traditional heating systems, application of different fuel types is possible. In total, 96 modernization scenarios were analysed (see more in section **3.5**). Additionally, analysis of lighting systems improvements was performed – it assumes replacement of traditional lightbulbs with LEDs. Ventilation system is set as unmodifiable because it is assumed, that for all the buildings airflow is constant (based on the building typology data) and uncontrolled (natural ventilation).

Four RES types were included in the performed analyses, accordingly solar, wind, geothermal and biomass. Out of the solar energy techniques, PV panels application was selected. PVs were defined using data for the average panel in 2018 or for the commercially available models. Wind energy potential was checked for both onshore and offshore turbine types, as well as for small vertical turbines integrated directly into buildings. Depending on the analysed localization of a BC, the availability of offshore wind turbines is limited (it is exclusive only for coastline cities – Gdansk, Leba and Szczecin). The offshore wind climate data were obtained from *FINO 2* – the research platform located at Baltic sea [383] founded and financed by [409], while for onshore scenario from the TMY files due to the lack of other data. The geothermal energy was examined using two different types of GHP models, available commercially. GHP applications are always associated with ground excavations (bottom heat source) and water-heated floor (upper heat source). Biomass was analysed basically as a supply fuel type for a heating stove – a pellet was assumed. Additionally, some theoretical application of batteries (energy storages) were considered – without comprehensive data of commercially available models. For energy storage systems either hybrid or on-grid models were assumed.

The performed analyses of BCs might be considered as an evaluation of potential refurbishments implemented following the LCC method (see more in section **2.5.1**). For all proposed modernizations a LCC analysis was performed, evaluating the economic profitability of the proposed refurbishment. Calculations were performed considering the period of 30 years, while the applied method is presented in section **3.7.6**. Therefore, the performed studies take into account both, energy and economic point of view. Moreover, the pursuit for energy-efficiency and economic profitability of a whole buildings cluster is significantly environmental-friendly, for local or even in national-scale.

In the dissertation LCA analyses are not included due to several reasons. Firstly, the LCA method is very complex and requires data, which is sensitive, sometimes even confidential. Secondly, it is extremely difficult to get all necessary nationally-approved EPDs, for all stages of each product life. Thirdly, the performed work is focused only on an operation phase (B) of a products life. Therefore, even if LCA analyses would have been performed, it would be incomplete – only 1 out of 4 phases of products life would be investigated. Consequently, it was decided to not perform LCA analyses in the dissertation, nevertheless, it is a great subject to implement in future studies of residential BCs.

3.3. EXTERIOR CLIMATE CONDITIONS OF THE SELECTED LOCALIZATIONS

Poland has five climate zones, characterized by a reference outdoor temperatures (θ_e), as shown in **Figure 3.3**. Each zone is characterized with reference outdoor temperature, which is the highest for the 1st zone (the mildest climate) and the lowest for the 5th one (the harshest climate). Reference outdoor temperature for each zone varies by 2°C, in a range from -16°C to -24°C.

Figure 3.3. *Climate zones of Poland (source: [359])*

Whenever more comprehensive analysis is considered, a detailed weather data is required. Presently, for numerous localizations, weather data files are available as TMY files. Those files consist of a set of meteorological data with the values for every hour in a year period for a given geographical location. Therefore, TMY weather files are designed to represent a typical yearly weather conditions at a particular location. TMY data are used in many fields to perform calculations that need meteorological data, especially for energy performance of buildings analysed with the usage of software like the *Energy Plus*.

The data are selected from hourly data measured in a longer period. Presently, there are numerous methods of constructing TMY files – the most popular types (formats) of weather files are accordingly:

- ISO format, based on [348];
- **W**eather **Y**ear for **E**nergy **C**alculations, Version **2** (WYEC2), design for ASHRAE [402] by *Watsun Simulation Laboratory*;
- **T**ypical **M**eteorological **Y**ear, Version **2** (TMY2), design by **N**ational **R**enewable **E**nergy **L**aboratory (NREL) [416];
- **T**ypical **R**eference **Y**ear (TRY), format proposed by ASHRAE [402].

The basis of each format is the same, *i.e.* the multi-year database, with weather measurements is required. For most methods period of 10 years is sufficient, besides TMY2 and WYEC2 formats, which require a 30-

year period. More information about different types of weather files can be found in [5]. Method selection is rather optional; it usually depends on local regulations.

The Polish database of weather files was obtained using the ISO method. Generally speaking, the selection for each month is based on some main weather parameters (total solar irradiation, dry-bulb temperature and relative humidity) and dependencies between them. Also, the average wind speed has an impact on the final data selection. A comprehensive overview of the method used for TMY definition for Poland was presented in [190]. Presently, for Poland, there are 61 defined weather files. These files were defined using a dataset from years 1971-2000 (sometimes with some lacks of measures). Due to the fact, that the used dataset is relatively old, simultaneously with constant climate change (global warming issue), a definition of new TMY files for Poland seems to be necessary.

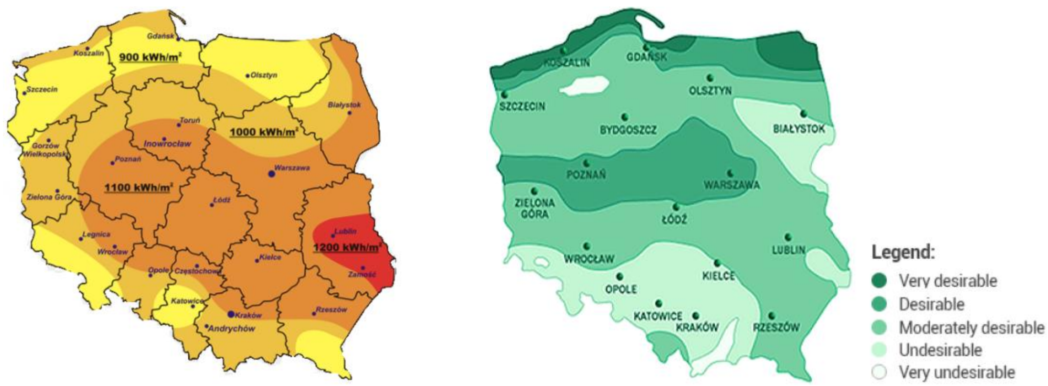


Figure 3.4. *Map of Polish climate: yearly sum of total solar irradiation (on left) and wind energy zones (on right) (source: [396])*

Using those 61 TMY files, we can define average climate parameters for Poland. Those values can be used to evaluate local climate conditions. The Polish climate summary, obtained using data from all 61 weather files is gathered in **Table 3.1**. Also, the summary of the main climate parameters for selected 10 locations was summarized in **Table 3.2**.

The above presented summary of Polish climate conditions can be used to predefine local climates for selected locations. The local climate analysis was performed to validate each location by comparing the temperature values as well as solar and wind conditions with average values for Poland (see **Table 3.3**). Using the performed collation some conclusions related to selected locations can be made. Gdansk, Szczecin, Pila as well as Wroclaw, Lodz, Warsaw and Cracow have statistically mild temperatures, while Bialystok is characterized by harsh conditions. Buildings in locations characterized with higher mean average temperature will require a lower amount of energy for heating purposes. Cracow and Rzeszow in particular, but also Wroclaw, Lodz, Warsaw has a favourable condition for solar installation applications.

Solar conditions are especially low in Leba and Szczecin. Nevertheless, even for the least advantageous location potential solar outputs can be profitable. Leba has the best wind conditions, followed by Gdansk and Warsaw. Surprisingly, Pila has wind conditions below the national average, as well as Wroclaw, Bialystok and Cracow.

Table 3.1. *Summary of Polish climate conditions based on available TMY files*

PARAMETER	VALUE
max. temperature (θ_{max})	36.50°C
min. temperature (θ_{min})	-26.20°C
mean temperature (θ_{mean})	7.75°C
max. total solar irradiation (ITH_{max})	1053.70 W/m^2
annual total solar irradiation (ITH_{sum})	935.54 kWh/m^2
mean solar irradiation during solar hours ($ITH_{SW,mean}$)	759.92 kWh/m^2
max. wind speed (WS_{max})	47.00 m/s
mean wind speed (WS_{mean})	3.25 m/s

Table 3.2. *Exterior climate data – summary for analysed localizations*

#	LOCALIZATION	θ_{min} [°C]	θ_{max} [°C]	θ_{mean} [°C]	ITH_{max} [W/m^2]	ITH_{sum} [kWh/m^2]	$ITH_{SW,mean}$ [kWh/m^2]	WS_{mean} [m/s]
1	GDANSK	-12.20	29.60	8.75	932.70	886.36	731.10	4.08
2	LEBA	-13.80	31.30	7.90	910.60	847.39	708.59	4.93
3	SZCZECIN	-13.50	30.00	8.82	928.10	862.99	714.09	3.45
4	PILA	-18.20	32.70	8.39	979.20	902.49	733.65	2.83
5	WROCLAW	-18.80	31.30	8.20	969.90	992.87	797.18	2.92
6	LODZ	-12.50	34.30	8.24	986.20	978.50	779.89	3.34
7	WARSAW	-12.30	33.20	8.26	911.80	977.93	779.07	4.00
8	BIALYSTOK	-17.60	30.80	6.92	967.60	897.14	710.81	2.53
9	CRACOW	-20.20	32.90	8.27	1031.60	1045.54	822.76	2.48
10	RZESZOW	-18.10	30.80	7.57	1038.60	1051.34	822.12	3.11

The profitability of offshore wind conditions is undeniable and was proven numerous times. Nevertheless, the assessment of onshore wind conditions requires more complex analysis rather than just a comparison of average wind speed. Despite the considered type of wind turbines, the wind conditions can be evaluated using calculated wind speed at the height of 100 m [100]. In a mentioned report, a wind power classes were defined, starting with poor resource potential (average wind speed at 100 m lower than 5.6 m/s) ending at superb resource potential (average wind speed at 100 m greater than 8.8 m/s). Wind speed at any height can be calculated using the equation (2.6). For wind power classes lower than 3 only small wind turbines (100 kW or less) might be profitable, while for classes higher than 4 large wind turbines are recommended.

$$V_h = V_0 \cdot \left(\frac{h}{h_0} \right)^{\alpha} \tag{2.6}$$

Table 3.3. *The comparison of local climates using mean temperatures as well as solar and wind conditions*

LOCATION	TEMP.	SOLAR	WIND
GDANSK	++	-	++
LEBA	o	--	+++
SZCZECIN	++	--	o
PILA	++	-	-
WROCLAW	+	+	-
LODZ	+	+	o
WARSAW	+	+	++
BIALYSTOK	--	-	--
CRACOW	+	++	--
RZESZOW	o	++	o

Where: '**--**': very adverse; '**-**': adverse; '**o**': average (neutral); '**+**': favourable; '**++**': very favourable; '**+++**': extremely favourable

The wind resources classifications for selected locations of Poland can be seen in **Table 3.4**. Out of analysed locations, only Leba has a high wind power class. Additionally, whenever we select a horizontal wind turbine, the frequency of wind directions should be considered. The wind turbine face should be always oriented to the most frequent wind direction, to maximize potential electricity generation. For Polish climate West and East directions are dominant. The wind direction frequency for the selected locations can be seen in **Figure 3.5**. Polish wind conditions were comprehensively discussed in [110]. According to the mentioned work, Poland has overall quite good wind conditions, with the favourable northern part of the country. The domestic (small) vertical wind turbines should be furtherly promoted to boost the national development of the wind power sector, which potential is promising.

Table 3.4. *Wind resources classification for analysed locations*

LOCATION	WS_{mean} [m/s]	$WS_{mean,50}$ [m/s]	WIND POWER CLASS	RESOURCE POTENTIAL
GDANSK	4.08	6.39	II	MARGINAL
LEBA	4.93	7.73	V	EXCELLENT
SZCZECIN	3.45	5.41	I	POOR
PILA	2.83	4.44	I	POOR
WROCLAW	2.92	4.58	I	POOR
LODZ	3.34	5.23	I	POOR
WARSAW	4.00	6.27	II	MARGINAL
BIALYSTOK	2.53	3.97	I	POOR
CRACOW	2.48	3.89	I	POOR
RZESZOW	3.11	4.87	I	POOR

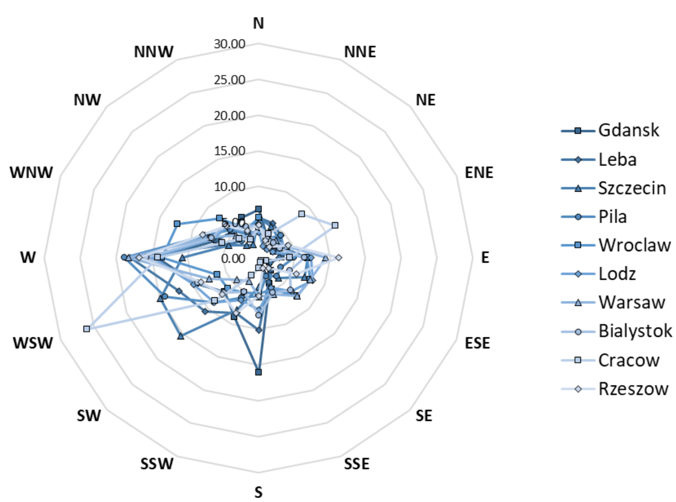


Figure 3.5. *Wind direction frequencies [%] for selected locations based on data from TMY files (own study)*

Advanced computational simulations can be a time-consuming activity, especially for complex building models. Those type of analyses typically need weather data, commonly in weather file formats, with hourly datasets of climate parameters. Sometimes, *e.g.* during design of heating or cooling installation power, we are interested only in results for extreme periods of the year. Those periods (typically named as design conditions) can be analysed using extreme summer (ESW) or winter weeks (EWW). The extreme weeks are characterized with the highest or lowest weekly mean temperature out of the whole year. Summary for both, ESW and EWW for the selected locations of Poland are presented in **Table 3.5** and **Table 3.6**. ESW occurs in late June, early or mid-July, as well as mid or late August, while EWW appears in December, January or early February. Simulations performed for one week are much faster than the ones performed for a whole year. Additionally, results for the one week are more transparent. Summarizing, depending on the purpose of performed analysis an appropriate simulation period should be selected for computation time optimization.

Table 3.5. *Exterior climate data of ESW – summary for analysed localizations*

#	LOCALIZATION	FROM	TO	θ_{min} [°C]	θ_{max} [°C]	θ_{mean} [°C]	ITH_{max} [W/m^2]	ITH_{sum} [kWh/m^2]
1	GDANSK	12.07.	18.07.	15.00	28.10	20.56	758.30	31.55
2	LEBA	01.07.	07.07.	11.40	24.90	19.92	910.60	35.65
3	SZCZECIN	06.07.	12.07.	10.60	29.40	21.24	754.80	39.72
4	PILA	23.06.	29.06.	11.30	31.70	20.59	712.90	40.33
5	WROCLAW	10.08.	16.08.	12.60	30.90	21.37	896.70	37.47
6	LODZ	15.08.	21.08.	14.60	34.30	22.99	856.00	37.50
7	WARSAW	03.07.	09.07.	13.40	31.30	22.41	909.50	43.15
8	BIALYSTOK	28.06.	04.07.	9.80	30.70	21.61	967.60	46.49
9	CRACOW	16.08.	22.08.	15.10	31.90	22.10	893.20	38.73
10	RZESZOW	16.08.	22.08.	14.60	30.80	21.89	901.30	40.59

Table 3.6. *Exterior climate data of EWW – summary for analysed localizations*

#	LOCALIZATION	FROM	TO	θ_{min} [°C]	θ_{max} [°C]	θ_{mean} [°C]	ITH_{max} [W/m^2]	ITH_{sum} [kWh/m^2]
1	GDANSK	10.12.	16.12.	-8.30	2.20	-1.24	262.80	3.99
2	LEBA	06.02.	12.02.	-13.80	3.00	-4.59	296.60	7.77
3	SZCZECIN	20.01.	26.01.	-10.60	0.00	-5.60	386.10	9.41
4	PILA	20.01.	26.01.	-13.00	-1.80	-6.85	393.10	10.50
5	WROCLAW	03.12.	09.12.	-12.70	3.60	-5.57	374.50	6.87
6	LODZ	20.01.	26.01.	-12.50	-1.30	-7.77	407.10	12.61
7	WARSAW	09.01.	15.01.	-12.30	-0.40	-5.94	364.00	7.34
8	BIALYSTOK	07.01.	13.01.	-17.60	-4.10	-9.73	341.90	5.01
9	CRACOW	21.12.	27.12.	-12.50	-0.30	-6.10	257.00	4.46
10	RZESZOW	08.01.	14.01.	-18.10	-4.00	-9.66	387.30	8.06

3.4. REPRESENTATIVE SFHS OF POLAND DEFINED BY MEANS OF THE *ENERGY PLUS* SOFTWARE

The object of performed analyses was a residential sector of Poland, or more precisely its biggest part – single-family houses. The archetypes of the single-family building stock of Poland was presented and discussed in the *TABULA* report [315], performed by NAPE. Based on the report, 7 representative SFHs of Poland were defined using the *Energy Plus* software. Those 7 types of RSFHs were already introduced in section **2.3.2**. Each of the defined house models were based on the data published in the *TABULA* report. Unfortunately, the published data is insufficient to validate defined buildings in the *Energy Plus* software. Therefore, the following construction assumptions were made:

- each building type has 2 occupied floors and unoccupied attic;
- buildings have no basements;
- each building is a square-based (length is equal to width);
- gable-type roof, 30 degrees sloped, W-E oriented;
- windows were placed directly in the middle of each wall, with lower edge 0.8m above the floor level, with a constant height of 1.4 m;
- doors were placed in the Northern wall;
- one bathroom was defined on each storey; the total area of bathrooms is equal to 10 % of A_o;
- there are no exterior shading systems.

Furthermore, the following non-construction assumptions were made:

- 4 residents per building;
- light activity (120 W/person ≈ 1.15 met) of the residents during the whole year;
- clothes resistance equal to 1.0 clo (approx. 0.155 m^2K/W) during the heating season and 0.50 clo (approx. 0.078 m^2K/W) for the rest of the year;
- living zones set point temperature set as 20°C;
- restrooms set point temperature set as 24°C;
- water radiators were used as a part of DH systems;
- operation schedules for occupants activity and installation work;
- the design load of a lighting system and equipment.

Considering the operation schedule, the typical schema of a family of four was used. Therefore, it was defined that for working days residents are away from their homes from 7:30 AM till 4:30 PM (half-hour for travel to work was assumed), while during the weekend, occupants stay indoors for a whole day (see **Figure 3.6**). It is almost impossible to define appropriate time-tables of residents' appearance in their homes, due to the huge variety of humans habits and everyday responsibilities. It is possible to perform a statistical analysis of a representative group of interviewees (using surveys) in order to define several typical operation schedules of households. Nevertheless, the most traditional schema (mentioned above) was used.

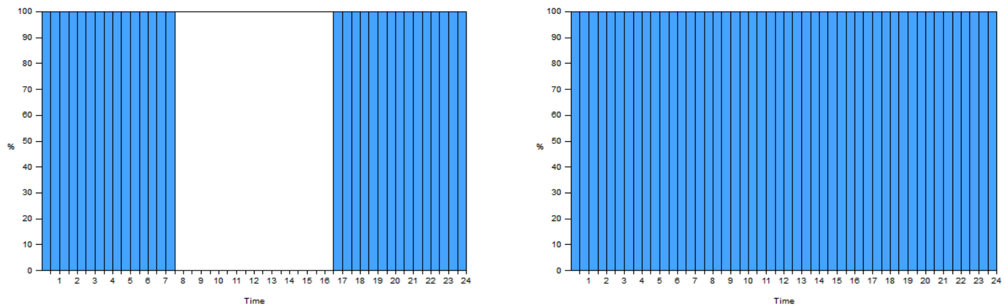


Figure 3.6. *Occupancy schedules for weekdays (on left) and weekends (on right)*

Energy consumption by household equipment is dependent on residents' habits and activities. The base value of energy demand by housing equipment equal to 8.0 W/m^2 was set according to data published by GUS [420]. Additionally, some of the equipment are still working (*e.g.* refrigerators, routers), while some are in standby mode while there is no occupants' activity (during their absence or sleeping hours). Therefore, it was assumed, that during periods when inhabitants are sleeping or they are outside the energy demand by housing equipment is at 1.2 W/m^2 (15 % of a base value). Defined schedules of housing equipment can be seen in **Figure 3.7**. It is aware of the fact, that defined schedules are rather idealistic – it is almost impossible to define energy demand profile by each house. Nevertheless, due to complexity and scale of the considered areas in the performed analyses the assumed schemas are considered as an acceptable approximation.

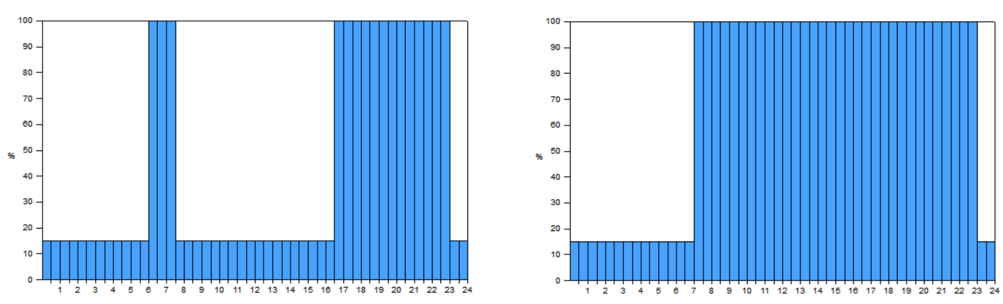
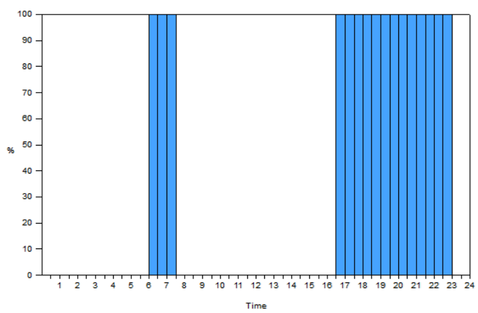


Figure 3.7. *Power density schedules of housing equipment for weekdays (on left) and weekends (on right)*

Considering the lighting system for households, several major aspects should be considered, particularly system operation hours, its necessity and design load. System availability is associated with occupants appearances – it is pointless to keep lights on in single-family houses whenever it is empty (besides the potential safety aspect). Therefore, the availability of lighting system was defined as shown in **Figure 3.8**.

Additionally, the necessity of keeping lights on is determined by the amount of natural light reaching the interior of houses. Therefore, a stepped lighting control approach was assumed, depending on the availability of natural daylight. The management system is based on discrete steps, with the electric power accessibility set to be off, 50 % on or 100 % on (the performed assumption is a tracing of typical light-switchers). Whenever the available daylight illuminance indoor is above 600 lux, the lights are off, in a range of 300-600 – 50 % on, and 100 % on for else cases. Finally, the electric power of the system is determined by means of the used type of lightbulbs. According to data published by GUS [420], it was assumed, that for a single-family house with traditional lightbulbs the system power level is equal to 12 W/m^2 and 4 W/m^2 for energy-efficient LED lightbulbs application. In both cases, target illuminance was set at 300 lux. Thus, for all the examined scenarios, always two variants of the lighting system were considered (with the traditional and LED lightbulbs). Obviously, it is recommended to replace traditional lightbulbs to energy-efficient LEDs in all households.



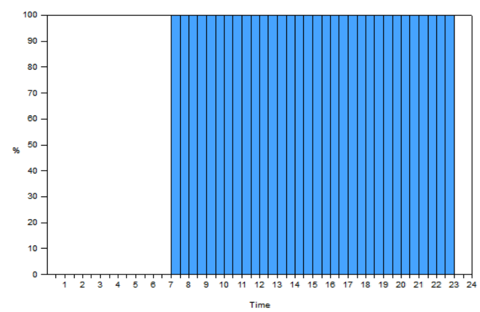


Figure 3.8. *Lighting system power density schedules for weekdays (on left) and weekends (on right)*

Some detailed data used during specifying the representative SFHs of Poland by means of the *Energy Plus* software are presented in **Appendix 2**, while their visualizations are presented in **Appendix 3**.

In the defined models, the DH system is available in periods Jan-May and Sep-Dec, 24/7. DHW system is available 24/7, for the whole year. Each house type has a system with different COP values and supply fuels, nevertheless, the installation schema remains the same – the defined schema can be seen in **Appendix 4**.

3.5. MODERNIZATION VARIANTS – OVERVIEW

In the performed analyses the following types of buildings modernizations were included:

- building refurbishment,
- heating system improvement,
- lighting system upgrade,
- application of RES.

In terms of buildings refurbishments, 4 scenarios were considered. First of them represents a base (reference) thermal parameters of a building enclosure, according to [315] – building components differ by means of U-value for each of 7 single-family house type. Remaining 3 scenarios significantly improve the thermal parameters of buildings enclosures, in order to fulfil the Polish regulations [346] for the year 2017 (BRV_1) and 2021 (BRV_2), as well as achieving passive standard (BRV_3) for the building components. For each of the mentioned variants, modernization is performed by means of adding thermal insulation layer for U-values decrease – different thickness of the additional insulation layer was required for each of the building types. Additionally, the considered variants assumed simultaneous refurbishment of exterior walls, ceilings, roofs and ground floors as well as replacement of building fenestration. EPS was used as an insulation material for exterior walls and ceilings, XPS for ground floors while mineral wool was applied in roofs. Constructions of the analysed parts of a building enclosure can be found in [315]. Modernization of a single partition was analysed only for the base variant (without consideration of building rotation and impact of the closest surrounding) for each building, to see how each component affects their overall energy profiles. Results were obtained for Wroclaw localization (which has the value of annual mean temperature closest to the national one) and are presented in **Table 3.7**, divided into individual building types. Additionally, all scenarios were presented for each modernization variant in one column, in the following order: BRV_1, BRV_2 and BRV_3.

It can be clearly seen that modernization of exterior walls (**EW**), in most cases, is the most profitable in terms of obtained reduction of heating energy consumption. For RSFH_1 and RSFH_2 (building types with the poorest thermal parameters of their enclosures) the modernizations are most beneficial in terms of heating energy savings. The highest reduction (approx. 61 %) was observed for modernization of **EW** of RSFH_2 up to the passive standard. Nevertheless, for most recent buildings (RSFH_6 and RSFH_7), modernization of **EW** is rather exiguous – the observed reduction varies in the range of 9-20 %. It is due to the fact, that those buildings are characterized with relatively good thermal parameters of their buildings' enclosures. For all the cases, modernization of ceilings (**C**) is the most profitable comparing with roofs (**R**) variants. That is because of the fact, that attics are assumed as unoccupied, unheated zones. Windows replacement (**W**) is not so profitable, nevertheless for RSFH_6 and RSFH_7 the meaningful energy reduction (in a range from 11 up to 19 %) can be observed. The observed savings are related not only to the thermal properties of buildings' fenestrations but also to windows size and their distributions – thus, for the most recent buildings potential reductions are higher. The least energy reduction potential variants are related to ground floor (**GF**) modernizations – the highest achieved reduction is only approx. only 6 %. Moreover, the complex thermal-renovation variants (**ALL**) were analysed, fulfilling BRV_1, BRV_2, as well as BRV_3 standards. Those solutions are the most beneficial in terms of potential reduction of heating consumption for all building types. The most significant reduction was obtained for RSFH_2, approx. 94 %. Such significant reductions were obtained due to the superior U-value of buildings' enclosures components, required for the analysed scenarios – especially for the passive standard, which additionally reduced amount of air infiltration (n_{inf}). Those comprehensive variants of buildings' enclosure modernizations are furtherly used in the presented studies of BCs, performed by means of the *TEAC* software.

Heating system modernizations can be divided into two categories: the first one that improves the COP of a traditional heating stove and the second one that replaces heating oven with a GHP. In the first scenario, old stoves are replaced with modern ones, supplied with gas with an overall heating system efficiency of 0.87 (HV_1). It is important to mention, that building types RSFH_5, RSFH_6 and RSFH_7 already have such heating system – that modernization did not affect them. Additionally, it was assumed that DH systems for RSFH_4 have COP of 0.87, not 0.86 as it is presented in [315]. Therefore, HV_1 modernization variant is also not considered for RSFH_4. Two commercially available GHPs were considered as additional modernization variants, accordingly with COP of 4.00 (HV_2) and 4.53 (HV_3). For both variants of GHP application, the supplementary amount of electricity consumption was included for auxiliary equipment which is necessary for proper operation of the applied system – it was assumed in accordance with [338]. For the purpose of performed analyses, it was assumed, that stoves supplied with biomass have the same efficiency as ones in HV_1 variant – therefore energy profitability is the same, with different environmental and economic impacts.

Buildings modernizations, which result in lowering heating energy consumption, were performed in combinations of building enclosure and heating system variants. Performed variants are presented in **Table 3.8** and **Table 3.9** (in first table for building types RSFH_1 – RSFH_3 and for RSFH_4 – RSFH_7 in the second one). In total, 96 scenarios were examined.

Table 3.7. *Comparison of heating consumption [kWh/a] for thermal-renovation variants of buildings' enclosures for Polish single-family houses stock*

	RSFH_1	RSFH_2	RSFH_3	RSFH_4	RSFH_5	RSFH_6	RSFH_7
BASE	26 358.97	32 035.03	24 303.63	23 245.02	11 716.66	7 989.15	9 661.17
ALL	3896.71	4 359.24	4 716.42	4 541.55	4 602.91	4 519.56	4 737.99
	3 399.75	3 652.06	4 247.39	3 929.94	3 941.37	3 873.23	4 013.29
	2 006.38	1 898.03	1 689.40	2 082.42	2 113.50	2 008.68	2 043.48
EW	11 803.09	13 688.34	13 795.04	9 722.57	8 486.60	7 240.78	8 731.15
	11 535.30	13 354.14	13 458.93	9 436.05	8 210.66	6 972.22	8 447.30
	10 949.11	12 620.10	12 741.04	8 818.52	7 614.60	6 398.77	7 830.85
C	23 296.62	27 678.82	22 229.78	20 056.25	8 761.21	5 520.43	7 096.25
	23 171.25	27 514.06	22 026.55	19 926.33	8 633.26	5 403.22	6 962.99
	22 862.38	27 114.15	21 550.47	19 614.94	8 378.68	5 132.95	6 646.04
R	24 618.74	30 149.03	23 857.75	21 891.09	10 065.32	6 744.61	8 625.63
	24 533.64	29 865.86	23 581.18	21 770.73	9 916.08	6 585.87	8 440.78
	24 390.67	29 647.88	23 329.28	21 553.84	9 629.34	6 282.32	8 084.24
GF	25 568.20	31 394.33	23 088.45	23 012.57	11 315.20	7 666.11	9 430.51
	25 568.20	31 394.33	23 088.45	23 012.57	11 315.20	7 666.11	9 430.51
	25 304.61	31 073.98	22 845.41	22 780.12	11 267.92	7 601.27	9 363.13
W	24 246.58	30 199.11	23 817.55	21 766.16	11 379.30	7 110.34	8 436.40
	24 098.44	29 971.39	23 574.52	21 567.80	11 092.70	6 950.56	8 060.01
	24 000.64	29 813.79	23 331.48	21 435.86	10 902.00	6 870.67	7 831.78

Where: **ALL** – all components renovated simultaneously; **EW** – exterior wall; **C** – ceiling; **R** – roof; **GF** – ground floor; **W** – windows

The remaining two types of analysed building modernizations, accordingly, lighting system modernization and application of solar or wind energy, concern the electricity consumption and its potential reduction. For each type of buildings, 2 variants of the different nominal power of lighting system were considered; the first one is a system with traditional lightbulbs, while the second one with energy-efficient LEDs (see more in section **3.4**). Due to the intermittency of RES, availability of a solar and wind energy needs to be analysed in their time of appearances. Some part of the produced electricity is used in real-time, while the rest of it needs to be stored or sold to the grid for later usage purposes. The mechanisms of applied time-dependent usage of RES are furtherly explained in subsections **3.7.4** and **3.7.5**. Solar and wind energy can be applied to all modernization variants.

As a result of performed analyses, almost all combinations of the above-mentioned modernizations are available. Some of the considered variants affect heating energy consumption, some electricity, nevertheless all of them are crucial for the assessment of economic and environmental profitability of the analysed BCs.

Table 3.8. *Combinations of the analysed renovation variants, valid for building types RSFH_1 – RSFH_3*

		HEATING SYSTEM MODERNIZATION VARIANTS			
		BASE	HV_1	HV_2	HV_3
BUILDING REFURBISHMENT VARIANTS	BASE	x	x	x	x
	BRV_1	x	x	x	x
	BRV_2	x	x	x	x
	BRV_3	x	x	x	x

Where: ‘**x**’ – selected for analysis

Table 3.9. *Combinations of the analysed renovation variants, valid for building types RSFH_4 – RSFH_7*

		HEATING SYSTEM MODERNIZATION VARIANTS			
		BASE	HV_1	HV_2	HV_3
BUILDING REFURBISHMENT VARIANTS	BASE	x	N/A	x	x
	BRV_1	x	N/A	x	x
	BRV_2	x	N/A	x	x
	BRV_3	x	N/A	X	x

Where: ‘**x**’ – selected for analysis; ‘N/A’ – not analysed

3.6. THE NN TRAINING PROCESS

The key module of the *TEAC* software is based on application of ANNs for heating demand predictions of areas constituting BECs. The AI application for various buildings energy-related analyses was introduced in section **2.8**. The defined NN considered some main characteristics of the selected representative buildings and built environment dependencies. For the defined network, the *Levenberg-Marquardt* (LM) method [86], [156], [172] (also known as the damped least-squares method) was applied. The LM algorithm was developed in the 1960s to solve nonlinear least-squares problems. The LM method is based on a gradient vector and a *Jacobian* matrix – it might be considered as a combination of two minimization methods: the *Gauss-Newton* and the gradient descent methods. The LM method works more like a gradient-descent method when the parameters are far from their optimal value, while when the parameters are close to their optimal value it acts more like the *Gauss-Newton* method. Due to the fact, that LM method is a hybrid approach it can be used to trade off the best features of different algorithms to solve a variety of problems. The LM algorithm is particularly effective in solving non-linear equations.

The structure of the used network is quite simple, nevertheless, it provides the best data regression with reasonably short calculation time for the analysed issue. The appositeness of the ANN structure was examined using different numbers of neurons within a single hidden layer – starting with 2 and ended with 24 following the procedure published in [248]. The final structure of the applied network includes 14 input neurons, 12 neurons within a single hidden layer and one output neuron (see **Figure 3.9**). The network was developed in three variants, depending on an analysed period (frequency) of energy prediction for hourly, daily and monthly input data. Depending on the selected case, an hourly heating demand or daily/monthly energy consumption for heating purposes was obtained as an output. The parameters used as inputs are listed below:

- the analysis time period frequency (**TP**) [-],
- outside temperature (**DBT**) [^{o}C],
- total sun radiation (**ITH**) [Wh/m^2],
- building heating area (**A_o**) [m^2],
- building volume (**V_o**) [m^3],
- total windows area (**A_{WIN}**) [m^2],
- air-change rate (**n_{tot}**) [1/h],
- U-value of exterior walls (**U_{WALL}**) [W/m^{2}K],
- U-value of roofs (**U_{ROOF}**) [W/m^{2}K],
- U-value of ground floors (**U_{FLOOR}**) [W/m^{2}K],

- U-value of windows (**$U_{WINDOWS}$**) [W/m^{2}K],
- heating system COP (**H_{COP}**) [-],
- building orientation variant (**OV**) [-],
- closest surrounding variant (**SV**) [-].

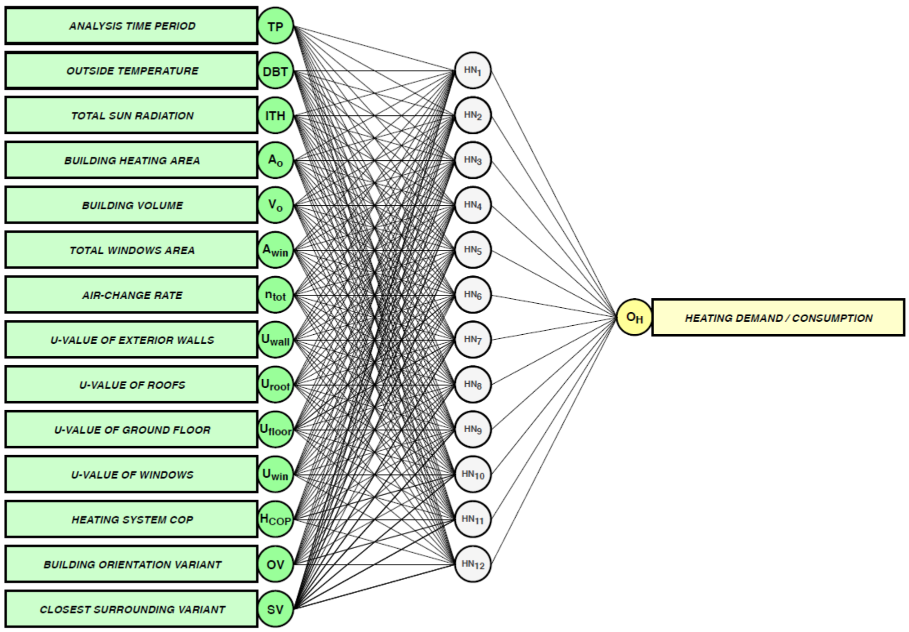


Figure 3.9. *The structure of defined NN (own study)*

The network was taught using the combinations of the above-mentioned parameters. The analysis time period frequency (TP) expresses time dependencies of climate data, as well as the obtained outputs. It was used to define three different types of analyses – monthly, daily and hourly approaches. Therefore, for each set of the input parameters (for each building within the analysed area), we will obtain 12, 365 or 8760 outputs. The climate parameters (DBT and ITH) are considered simultaneously, based on the selected localization – ten variants were considered. Nevertheless, thanks to the selection of various localizations throughout the territory of Poland, the significant range of exterior temperatures (which can be considered as a representative array for the Polish climate) were included in the performed analyses (see **Figure 3.10**). Each building geometry was defined using their heating area (A_o), volume (V_o) and windows area ($A_{WINDOWS}$) – thus seven variants of mentioned parameters were included, considered instantaneously for each building type. Those geometry parameters might be replaced by just one input data, expressing the building type, nevertheless, it was decided to use a more complex approach of the building geometry description in case of possible future studies concerning geometry variations (thanks to that, the network might be further upgraded). Four of the variants related to buildings' enclosures parameters were included, accordingly the base option, and specifications obligatory in Poland for years

2017 and 2021 [346], as well as for the passive standard. Ten different values of the heating system COP were used; eight for traditional schema with heating stove and two for scenarios with GHP application. The both GHPs variants were based on commercially available products, while COP values range for traditional heating stove system were set according to the data published in [315] (from 0.59 to 0.87), varied by 0.04. Thus it is possible to define a modern building type (*e.g.* RSFH_5) with less efficient heating system comparing with the statistical data. Additionally, eight different building orientations were checked, varied by 45 degrees. Moreover, sixteen scenarios of the closest building surroundings were included (see **Appendix 5**). In total, 358 400 sets of input data (with 14 columns each) were used for the NN learning process. Each of the used set consisted of:

- for an hourly-frequency network: 3 139 584 000 rows,
- for a daily-frequency network: 130 816 000 rows,
- for a monthly-frequency network: 4 300 800 rows.

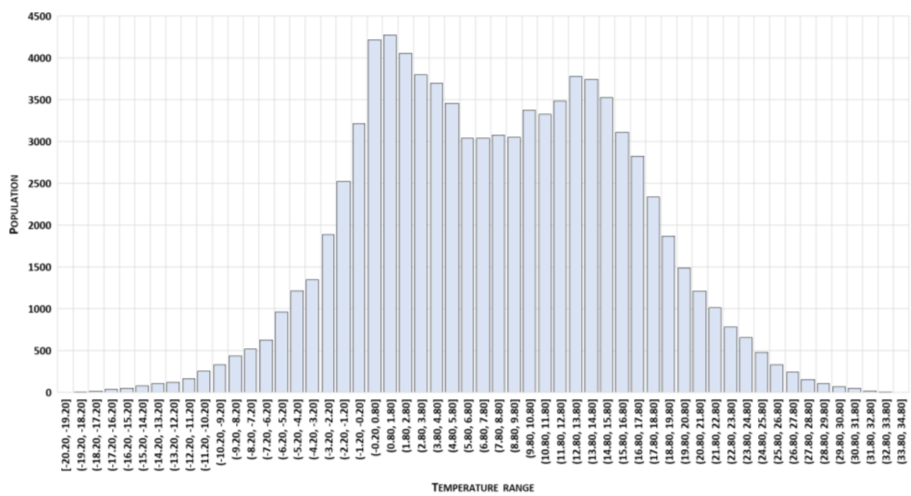


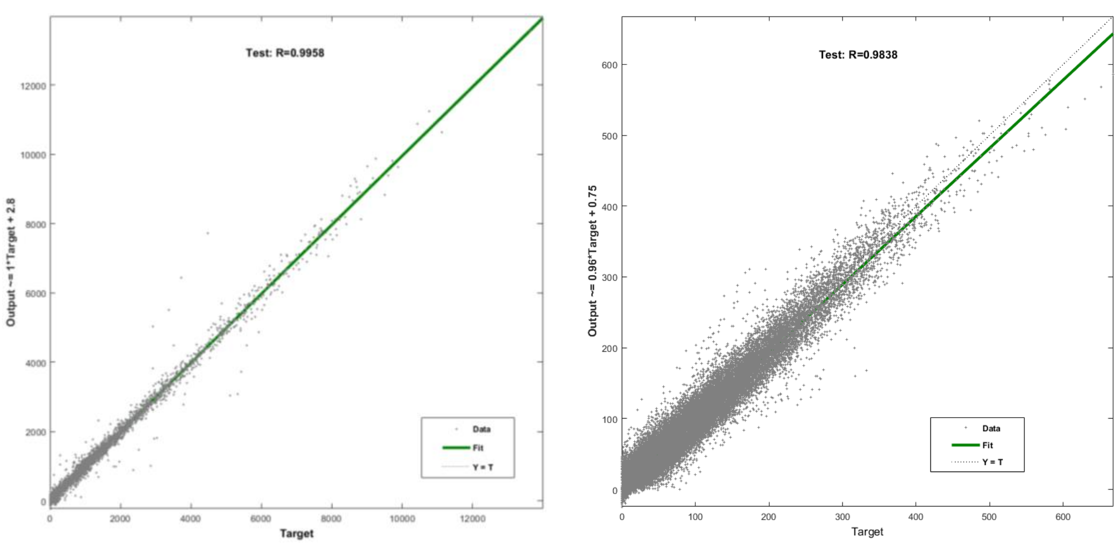
Figure 3.10. *Exterior temperature (DBT) histogram for the selected localizations of Poland (own study)*

An interesting fact is that for the purpose of performed analyses, which are valid for Polish representative single-family houses, the defined NN might be simplified. Building geometry parameters might be replaced using just one input, expressing building type. This is also valid for thermal parameters of buildings' enclosures because all the partitions are considered collectively. Therefore, it is possible to obtain similar NN with a simpler structure – with just 8 input neurons. Nonetheless, it is planned to further improve the defined network – thus, the selected method is considered as an appropriate one. The used approach provides the potential universality of the network for a significant variety of single-family houses.

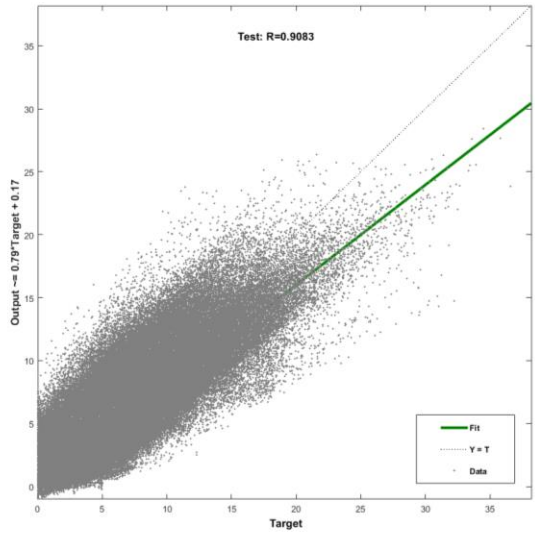
The training process was performed using the *Matlab* software [389]. The *Matlab* software was used only during the training process due to its friendly GUI. After obtaining the trained NN, it was re-written into

Python language (the code is presented in **Appendix 6**) – therefore heating energy demand predictions are performed directly by the *TEAC* software. All data used in NN analyses (both inputs and outputs) were divided into 3 groups of samples: training, validation and testing set, in constant shares of respectively 70, 15 and 15 %. Training data is used to test the network (adjusted according to its error). The validation set of inputs is used to measure network generalization – the training process halts whenever generalization stops improving. The testing data does not affect the training process – it is used only to provide an independent measure of network performance. In **Figure 3.11** the training results were shown. The presented graphs show regression plots for the test group of samples (for each calculation period) for the data used for learning purposes. A very good match was observed for monthly and daily predictions – regression coefficient (R) for test data equals to 0.9958 and 0.9838, accordingly, and a good one for hourly study – R equals to 0.9083.

The precision of the trained network was additionally checked by additional validations using some results obtained by means of the *Energy Plus* software. The validation process is presented in subsection **3.7.2**. The defined NN is efficient in heating demand predictions of Polish representative single-family houses with a satisfactory accuracy.



A) B)



C)

Figure 3.11. *Regression plots for the test data of neural network analysis for different calculation periods: **A**) monthly, **B**) daily and **C**) hourly*

3.7. THE *TEAC* SOFTWARE DESCRIPTION – MODULES OVERVIEW

The Computer **T**ool for **E**nergy Efficiency **A**nalysis of an Energy **C**luster (*TEAC*) is a research software allowing to perform UEM analyses of BC areas. The *TEAC* software is suitable for Polish residential buildings stock studies, based on the single-family houses typology (described in subsection **2.3.2**). The developed tool is unique due to its' ability of detailed analysis of areas consisting of numerous buildings, by means of time-distributed results. Also, thanks to the application of a NN (see more in subsection **3.7.2**), a huge advantage of the *TEAC* software is the quickness in obtaining results for a large areas analysis. It is important to mention, that further development of the *TEAC* software is relatively easy to perform. The software might be improved by upgrading of some modules, as well as by training with some additional buildings data, especially other building types typology or archetypes for other countries.

The detailed *TEAC* software schema (step-by-step procedure) can be seen in **Figure 3.12**. The developed tool was codded mainly in the *Python* programming language, including application of the *Matlab* software (used for ANN definition and training) and it uses *csv*-type files as database storages. The *TEAC* software consists of 4 major modules and 7 submodules, accordingly:

- **Module 1**: area definition;
- **Module 2**: ANNs application for heating demand predictions;
- **Module 3**: results:
    - default (LDCs, mapping, consumption data);
    - optional (solar and wind energy, economic analysis and emissions);
- **Module 4**: outputs export.

Each of the defined modules will be briefly described in the following sections. Additionally, the test of *TEAC* software application was presented for two relatively simple examples, in order to check its' results (see section **3.8**). Next, comprehensive examples of a *TEAC* software application were presented in chapter **4**. Those BCs consist of hundreds of buildings, defined using different modelling approaches available in the code.

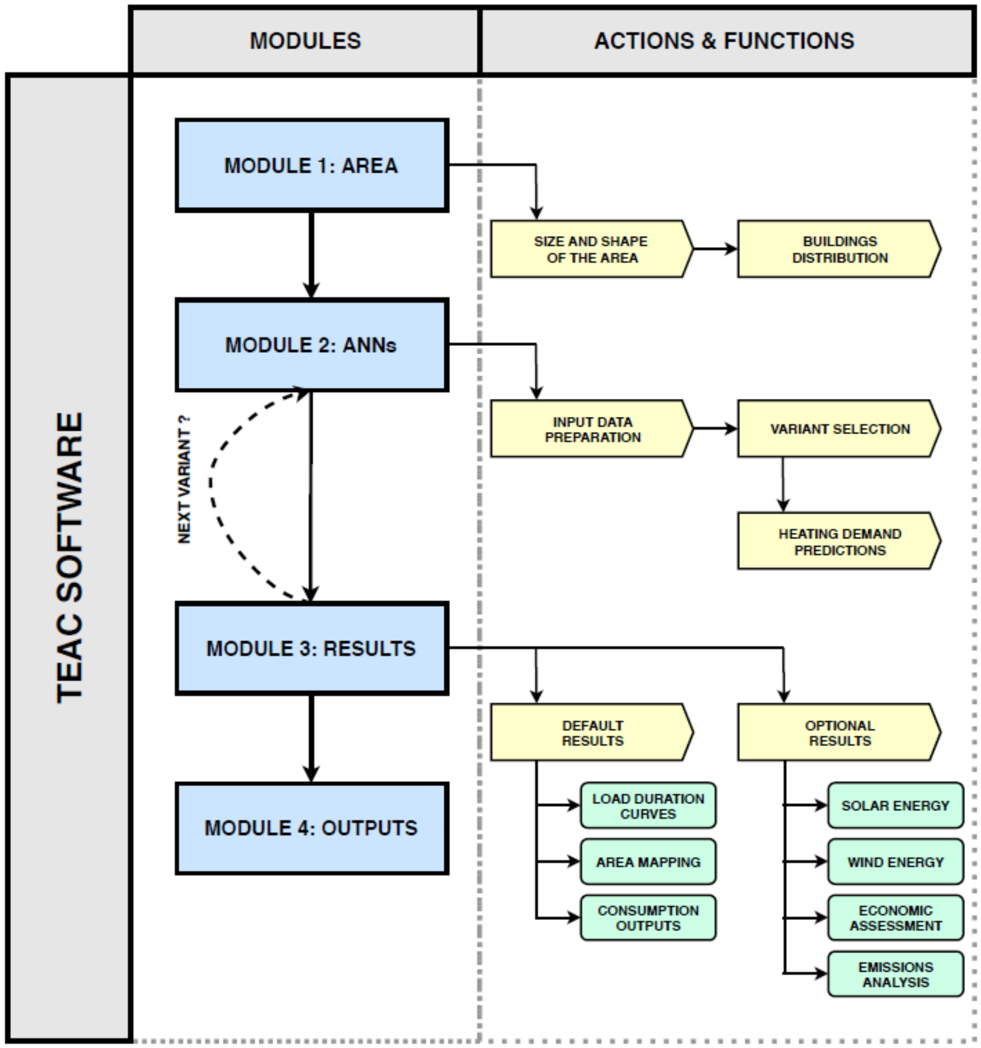


Figure 3.12. *A comprehensive schema of a modular structure of the TEAC software (own study)*

3.7.1. AREA DEFINITION MODULE

The first step in the *TEAC* software is to define size and structure of the analysed area. At the beginning we need to define a size of the area, using horizontal (X_A) and vertical (Y_A) number of parcels – each parcel (considered as a building plot) is always square-based, 30x30m (see **Figure 3.13**). The size of a single parcel was assumed based on data published in urban development plans for Lodz. Therefore, the total size of the analysed area is a product of a X_A or Y_A and 30m (the parcel edge length).

Additionally, even if we are investigating a non-regular shaped area we need to define the region as a rectangle, and next define buildings placements manually (currently, the only approach to define non-uniform regions). As it was already mentioned, it is assumed that each building is placed directly in the centre of a parcel, one in each cell only. The *TEAC* software performs numbering of buildings constituting the analysed area automatically (as presented in **Figure 3.13**).

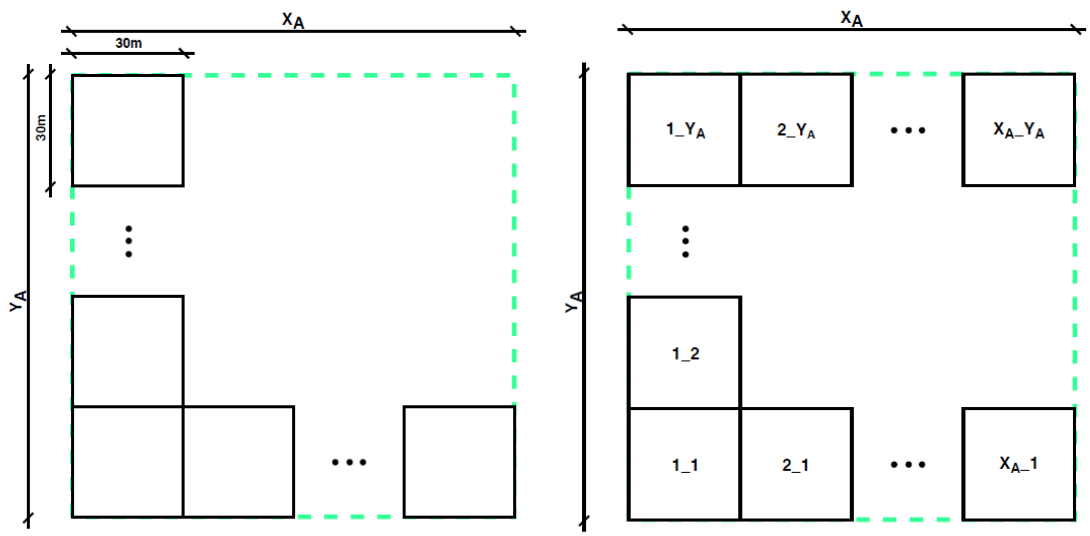
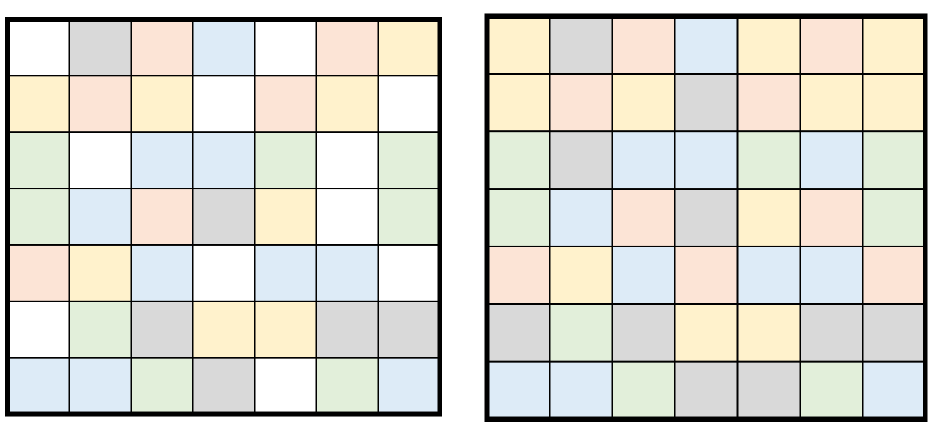


Figure 3.13. *The schema of the analysed area size definition (on left) and parcel numbering method (on right)*

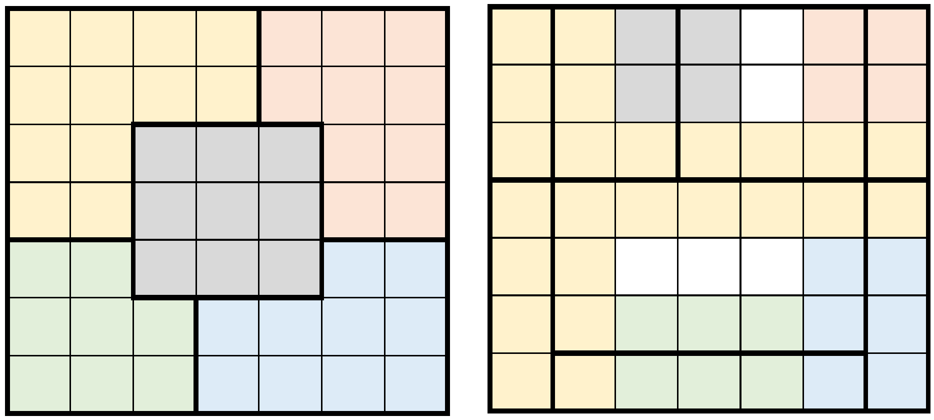
The building's placement is always performed in two steps: selecting a building type (or empty cell) in each parcel followed by setting the object orientation. There are 8 variants of building orientation, starting with the base orientation in accordance with the geometry data and area coordination – North direction is always acquiescent the course of increasing value on the vertical axis. Orientation variants vary by 45 degrees, rotated clockwise. There are 4 different, pre-defined methods of buildings distribution definition in the *TEAC* software (see **Figure 3.14**):

- manual (**DT1**),
- random (**DT2**),
- based on old cities growth plan (**DT3**),
- based on streets grid (**DT4**).



A)

B)



C) D)

Figure 3.14. *Available neighbourhoods built environment schemes in the TEAC software: A) manual selection (**DT1**); B) random buildings placement (**DT2**); C) old city development type (**DT3**); D) city-streets placement development (**DT4**, main streets highlighted with bold line); each colour represents one group of buildings, white spots symbolize empty parcels*

The first option, manual definition (**DT1**), requires a handheld definition of all parcels composing the analysed area. For each cell, it is necessary to select a building type and its orientation. Using **DT1** method it is available to define an empty parcel – therefore, it is possible to define a unique urban structure. It is the best approach in order to define the analysed area comprehensively, on the other hand, it is the most time-consuming method whenever larger BC is examined. The second option, random selection (**DT2**), performs an random placement of all buildings composing the analysed area and selects randomly their orientations. Using this option all parcels are occupied – there are no empty plots. The **DT2** approach is the simplest and fastest method of region definition using the *TEAC* software, nevertheless, user has no control on buildings selection. The last two models of buildings distribution are modelled based on a built environment of city-regions. The third approach (**DT3**) represents cities with old downtowns, which are typically located directly in their centres; along with city development, modern districts are usually constructed radiantly. A user needs to define the size of the neighbourhood as well as its' building types – only one group of buildings is allowed in each quarter. Each zone needs to be defined using rectangle-based areas, using two parameters: diagonal symbols of external parcels included in the neighbourhood. Therefore, whenever a complex shape of the analysed quarter is considered (*e.g.* L-shape) it is necessary to define several zones for a single zone. The orientation of each building in the zone is selected automatically. It is possible to include empty parcels within defined quarters, nevertheless, their positioning is random (number of empty cells is required as an input). An example clarifying how to define the analysed area using **DT3** approach is presented in **Figure 3.15** (on left). The exemplary area consists of 5 neighbourhoods, indicated by different colours. Yellow, green and grey zones are defined using only 2 parameters (cells indexes), expressing corner parcels. Remaining two areas (orange and blue) are L-shaped, and for their proper definition, it is required to divide them into two rectangle zones (highlighted using bold lines). Whenever undefined cells remained, the *TEAC* software will automatically consider those parcels as empty ones. The last option of buildings distribution definition (**DT4**) allows defining a built environment by means of roads grid – both in horizontal and vertical directions. The concept was inspired by the actual city streets grid model. Using **DT4** approach is similar to the **DT3** method – it is required to define buildings placement on either one or both sides of the road. Remaining, not defined cells are considered as empty ones. An important limitation is that whenever **DT4** approach is used it is impossible to define more than 2 rows or columns at once – it illustrates the actual state of buildings placement next to the road (access to only one building on each road side). The **DT4** method is presented in **Figure 3.15** (on right). Following this method an input for a single building is presented below.

{X_i_Y_i, *building type*, *building orientation*}

An exemplary input can be seen below.

{1_1, *RSFH_1*, 3} or {1_1, 1, 3}

Summarizing, regardless of the selected approach one is obligated to define the size of the analysed area, and then to include buildings placements. For each of the defined group of buildings (quarters, streets) only one building type can be selected. In the most methods (besides **DT1**) buildings orientation is selected randomly. Yet, in order to maximize the mapping of the analysed residential region, the **DT1** method is recommended. It is the most time-consuming approach available in the *TEAC* software, but it allows to define non-uniform neighbourhoods, with appropriate (not randomly selected) orientations of each building constituting the analysed BC.

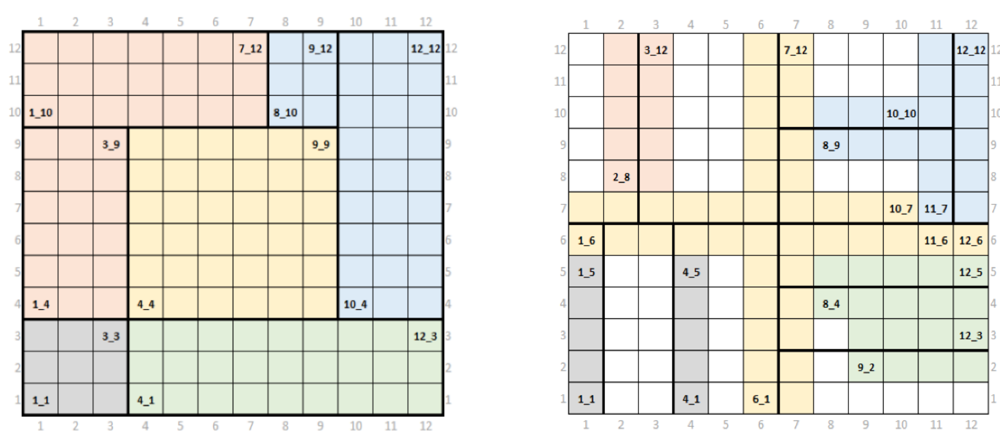


Figure 3.15. *Example of area definition in the TEAC software, using* ***DT3*** *(on left) and* ***DT4*** *(on right) method*

Considering the placement of buildings within the analysed area it is necessary to include the impact of shading by some nearby objects. To include the impact of the closest surrounding each building is analysed including surrounding objects (see **Figure 3.16**). Based on buildings placement within the analysed region, or more precisely each of the defined parcels, the *TEAC* software is capable to automatically assign all necessary parameters required for valid calculations including shading impact. For the mentioned purpose, the analysis of the closest surrounding is performed, using blocks, which represent other buildings. The blocks were placed directly in the middle of the neighbouring parcels, the same way as the analysed buildings. The blocks are not rotated – their side surfaces (which expressed exterior walls) faced main directions. The defined blocks are cuboids, with a square base, 11x11m, with a total height of 8m. The selected dimensions ensure the most unfavourable conditions – cuboid is bigger than the largest building out of Polish single-family houses typology. In total, sixteen variants of the closest surrounding are considered as presented in **Appendix 5**. Summarizing, based on the predefined BC (using size and buildings placement) the *TEAC* software selects the appropriate variant of the closest surrounding of each building within the analysed area.

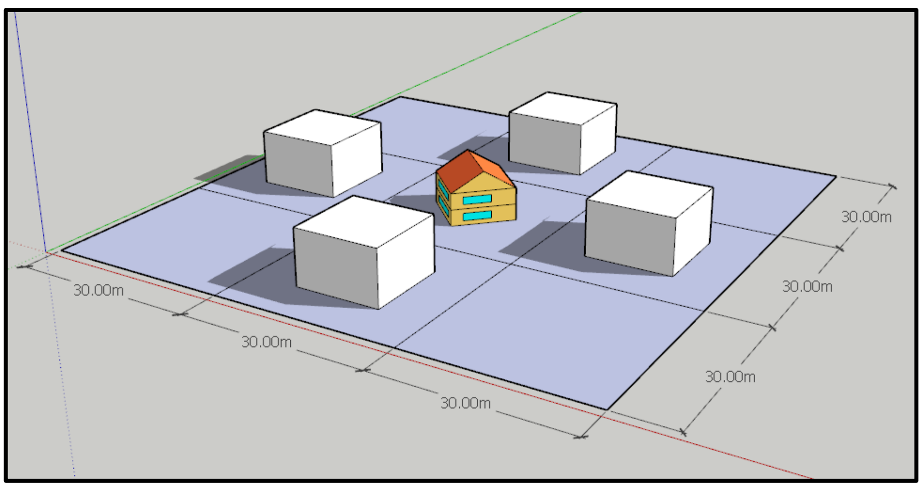


Figure 3.16. *An exemplary visualization of building placement and its' orientation with consideration of the closest surrounding impact used in the TEAC software*

3.7.2. HEATING DEMAND PREDICTION – APPLICATION OF AI

Heating demand predictions are performed using the trained NN (see more in section **3.6**). The network was trained using the LM method, based on the simulation results obtained by means of the *Energy Plus* software. All the gathered data refer to the Polish single-family household sector.

Application of the network is rather simple, nevertheless, it requires some effort during input data preparation. The input data should be saved in a **.csv* file, following the schema presented in **Table 3.10**. The positioning of each parameter, as well as the appropriate total number of values (case-dependent), is crucial. Each value should be separated using a comma, while each line should be ended with a semicolon.

A proper **.csv* file should look like the column '*Base*' or '*Renovated*' in **Table 3.10** (without parameter symbols; only values).

Table 3.10. *An exemplary set of parameters used as input data for the NN prediction process*

PARAMETERS *	*BASE*	*RENOVATED*
TP [-]	1, 2, 3, ..., 8760;	1, 2, 3, ..., 8760;
DBT [°C]	0.60, 0.70, 0.70, ..., -1.20;	0.60, 0.70, 0.70, ..., -1.20;
ITH [W/m^2]	0.00, 0.00, 0.00, ..., 0.00;	0.00, 0.00, 0.00, ..., 0.00;
A_o [m^2]	134.31, 134.31, ... 134.31;	134.31, 134.31, ... 134.31;
V_o [m^3]	330.80, 330.80, ..., 330.80;	330.80, 330.80, ..., 330.80;
A_{WIN} [m^2]	23.10, 32.10, ..., 23.10;	23.10, 32.10, ..., 23.10;
n_{tot} [1/h]	0.60, 0.60, 0.60, ..., 0.60;	0.60, 0.60, 0.60, ..., 0.60;
U_{WALL} [W/m^{2}K]	1.18, 1.18, 1.18, ..., 1.18;	0.20, 0.20, 0.20, ..., 0.20;
U_{ROOF} [W/m^{2}K],	0.65, 0.65, 0.65, ..., 0.65;	0.15, 0.15, 0.15, ..., 0.15;
U_{FLOOR} [W/m^{2}K]	1.75, 1.75, 1.75, ..., 1.75;	0.30, 0.30, 0.30, ..., 0.30;
$U_{WINDOWS}$ [W/m^{2}K]	2.75, 2.75, 2.75, ..., 2.75;	1.10, 1.10, 1.10, ..., 1.10;
H_{COP} [-]	0.59, 0.59, 0.59, ..., 0.59;	0.87, 0.87, 0.87, ..., 0.87;
OV [-]	3, 3, 3, ..., 3;	3, 3, 3, ..., 3;
SV [-]	14, 14, 14, ..., 14;	14, 14, 14, ..., 14;

***** used symbols were introduced in section **3.6**

At the beginning of the input data preparation process, it is necessary to define the type of study. As it was already mentioned, the *TEAC* software is capable to predict either hourly or daily or monthly heating demand. Next, the climate data (one for one study) should be defined. The climate conditions can be loaded out of the analysed localizations or be defined by the user. After that, it is required to use already input data defining the analysed area (see more in subsection **3.7.1**).

The approach of input data preparation is dependent on the method of buildings distribution definition used in the previous module of the *TEAC* software. The random option selection simplifies the whole procedure, nevertheless, there is no control on buildings selections. On the other hand, the manual option requires defining of every single building – which is time-consuming. Therefore, a solution for quicker (and easier) data preparations was defined, using keywords. Firstly, the analysed study needs to be defined, expressed by time period – in the *TEAC* software we are typing '*hourly*', '*daily*' or '*monthly*'.

An exemplary line, expressing input data performed using the manual method, for a single building is presented below (more examples can be seen in section **3.8** and **Appendix 7**). It can be seen, that the *TEAC* software is using building's coordinates in order to load the analysed object parameters. Each colour represents one group of parameters.

{hourly, Lodz, 1_1, base, base}

Whenever the input data file is finished, the *TEAC* software searches for appropriate parameters expressing the defined scenario. The final input (several lines, each line is indicated with {} symbols) is generated and saved as a **.csv* file and then furtherly used for NN prediction process. The final output might look as presented below.

{1, -4.30, 0.00, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 225, 6};

{2, -4.10, 0.00, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 225, 6};

{3, -4.00, 0.00, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 225, 6};

...;

{8760, 0.20, 0.00, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 225, 6}

As it was already said, it is possible to express the used parameters by means of keywords and symbols (see **Table 3.11**). Below there is a description of how to define an exemplary building out of the analysed area. For the purpose of explanation, the monthly analysis (**M**) is selected in the first step. In the second step, localization needs to be defined – Lodz (**6**) is selected. Because the analysis is for the monthly frequency, the *TEAC* software automatically loads the mean monthly temperatures and the sum of solar radiation as the climate condition parameters. The above mentioned first two steps are valid for all buildings constituting the analysed area. In the third step, we need to select each building, one by one, in order to define missing parameters for the whole region. It is important to mention, that the building geometry parameters ($\mathbf{A_o}$, $\mathbf{V_o}$, $\mathbf{A_{WIN}}$), as well as the orientation (**OV**) and surrounding variants (**SV**), have been already defined during the area description phase (see more in subsection **3.7.1**). For the purpose of this example, RSFH_3 (**3**) is selected, located in the left-bottom corner of the area (**3**), oriented by 135 degrees (**3**). The fourth step requires selection of the buildings' enclosures variant; in this example base variant (**0**) is selected. The final fifth step needs the parameter to define heating system – for this sample base variant (**0**) is selected. In this step, the values allowed by the *TEAC* software are: 0.59, 0.63, 0.67, 0.71, 0.75, 0.79, 0.83, 0.87, 4.00, 4.53 – all other values are unavailable. The fourth and fifth steps are needed for all the buildings within the analysed area.

Table 3.11. *All the keywords available in NN application module of the TEAC software*

GROUP OF PARAMETERS	KEYWORDS	DEFINED PARAMETERS
ANALYSIS TYPE	*'hourly'* (**H**), *'daily'* (**D**), *'monthly'* (**M**)	**TP**
CLIMATE CONDITIONS *	*'manual'* (**M**), *'Gdansk'* (**1**), *'Leba'* (**2**), *'Szczecin'* (**3**), *'Pila'* (**4**), *'Wroclaw'* (**5**), *'Lodz'* (**6**), *'Warsaw'* (**7**), *'Bialystok'* (**8**), *'Cracow'* (**9**), *'Rzeszow'* (**10**)	**DBT**, **ITH**
BUILDING GEOMETRY	*'RSFH_1'* (**1**), *'RSFH_2'* (**2**), *'RSFH_3'* (**3**), *'RSFH_4'* (**4**), *'RSFH_5'* (**5**), *'RSFH_6'* (**6**), *'RSFH_7'* (**7**),	A_o, V_o, A_{WIN}
BUILDINGS ENCLOSURES	*'base'* (**0**), *'BRV_1'* (**1**), *'BRV_2'* (**2**), *'BRV_3'* (**3**)	n_{tot}, U_{WALL}, U_{ROOF}, U_{FLOOR}, U_{WINDOW}
HEATING SYSTEM	*'base'* (**0**), *'value'***	H_{COP}
ORIENTATION VARIANT ***	*'random'* (**R**), ***'0'***, ***'1'***, ***'2'***, ***'3'***, ***'4'***, ***'5'***, ***'6'***, ***'7'***	**OV**
SURROUNDING VARIANT	****	**SV**

Where: * defined only once, for the whole process; ** actual value needs to be input; *** already defined during the analysed region size; **** based on coordinates of the analysed building

Below, the final form of exemplary definition of a sample building generated for NN monthly prediction process.

{1, -1.00, 27962, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 3, 3};
{2, -1.00, 31503, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 3, 3};
{3, 3.30, 73137, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 3, 3};
{4, 7.60, 99324, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 3, 3};
{5, 13.50, 155522, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 3, 3};
{6, 16.60, 150700, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 3, 3};
{7, 17.50, 146603, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 3, 3};
{8, 17.90, 124786, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 3, 3};
{9, 12.90, 76655, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 3, 3};
{10, 6.60, 51570, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 3, 3};
{11, 3.80, 22963, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 3, 3};
{12, 0.70, 17769, 134.31, 330.80, 23.10, 0.60, 1.18, 0.65, 1.75, 2.75, 0.59, 3, 3}

The validation was performed to check, if the trained NN is capable to predict, with a sufficient accuracy, heating demand of Polish single-family sector. The validation process was done for 3 scenarios, based on the variability of climate conditions, building geometry data and heating installations efficiency. The main focus was put on examinations of the weather parameters, particularly the exterior temperature values. At this point, the main target of the defined NN is to predict heating demand for conditions characteristic for Polish climate (regardless of the analysed localization). Temperatures' range and variety of values within that assortment are sufficient to execute accurate predictions for optional exterior temperature values within the range. In practice, the trained network is capable to perform heating demand predictions of Polish single-family houses sector for the majority of localizations in Poland (aside from extremely harsh places in terms of their climates, such as Zakopane city). Some exemplary validations are presented in **Figure 3.17**, for one week period (for results legibility). EWW periods were selected, as the coldest times of the year. Those exemplary results were obtained for RSFH_4 building type. In all the cases, very good accuracy was obtained, despite the fact, that the used TMY weather data was different than 10-preselected ones – records for cities Czestochowa, Gorzow Wielkopolski and Olsztyn were used. An interesting fact is that the network has predicted heating demand almost perfectly in meaningful moments (peaks), while it has some problems with very low values (lower than 0.5kW). Nevertheless, the mentioned issue is not an obstacle for the conclusion, that the defined network is an effective tool for the heating demand predictions for Polish climate conditions. Some additional collation of the performed study is presented in **Table 3.12**.

Table 3.12. *Comparison of results obtained by means of the Energy Plus and the defined network*

		BASE VARIANT		BRV_2	
		E+	***TEAC***	**E+**	***TEAC***
CZESTOCHOWA	HD_{max} [kW]	11.98	13.03	3.11	3.55
	HC_{EWW} [kWh]	1489.34	1480.53	366.58	331.39
	HC_A [kWh/a]	23593.90	25661.56	4423.06	4794.51
GORZOW WIELKOP.	HD_{max} [kW]	11.52	12.39	3.13	3.53
	HC_{EWW} [kWh]	1491.81	1496.99	408.60	367.93
	HC_A [kWh/a]	23083.23	24824.24	4410.04	4760.01
OLSZTYN	HD_{max} [kW]	11.82	11.30	3.22	3.29
	HC_{EWW} [kWh]	1235.38	1102.17	298.51	261.58
	HC_A [kWh/a]	27149.09	25961.23	5622.02	5957.98

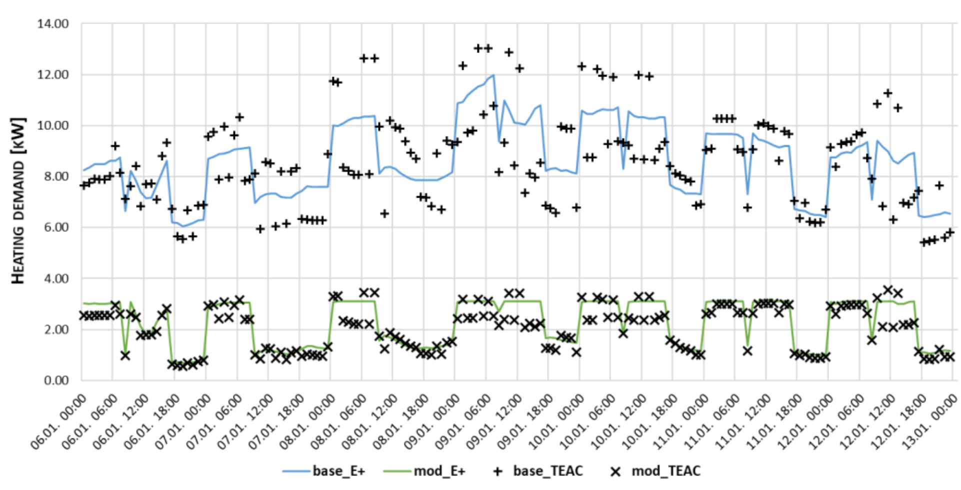
Where: **E+** – the *Energy Plus* software; HD_{max} – maximal heating demand; HC_{EWW} – heating demand for EWW period; HC_A – annual heating demand

As can be seen, a sufficient accuracy in terms of predictions of hourly heating demand distribution has been achieved for the analysed scenarios. The defined network is predicting the time-trend of demand distribution properly, nevertheless, there is no rule if the predicted values are below or above the expected ones, obtained by means of the *Energy Plus* software. For most of the cases of base buildings variants (before refurbishments), the NN is overestimating the expected values, while for the thermo-modernized scenarios underestimating them. For the presented validation the annual heating consumptions (HC_A) have been predicted with accuracy (expressed as percentage of the absolute values) in the range of 4.38-8.76 % compared to the results obtained by means of the *Energy Plus* software. The peak values of heating demand (HD_{max}) are also predicted with a sufficient accuracy, in the range of 2.17-14.15 %.

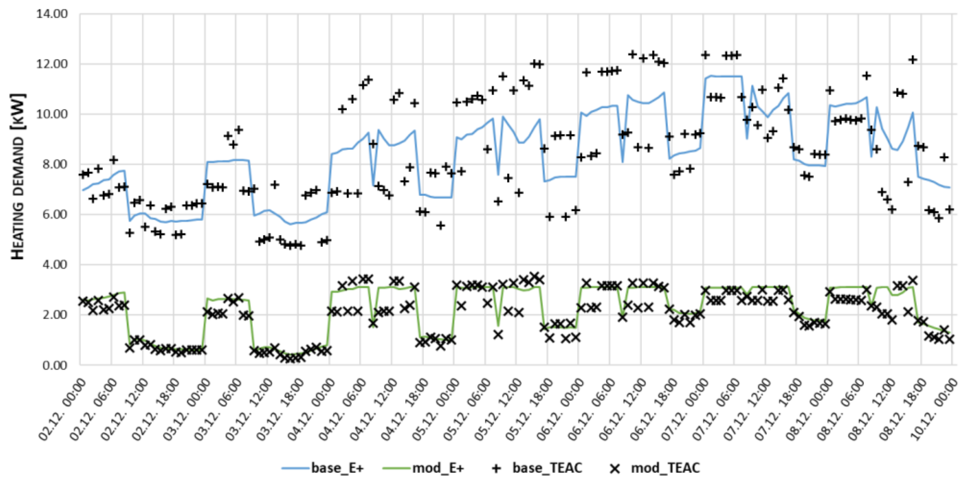
For the parameters defining buildings' geometry and their enclosures only several values were checked, which are valid for the representative single-family houses of Poland. Therefore, it is impossible to perform accurate heating demand predictions for values different than those in the defined dataset. Validation attempts using the buildings data (accordingly occupied area, volume and windows area) outside the defined range were characterized with insufficient accuracy comparing with the results obtained by means of the *Energy Plus* software. Thus, at this moment, the defined network, as well as the *TEAC* software, are valid only for the representative single-family houses of Poland. It is planned in the nearest future to improve the present network for a larger variety of buildings. After successful adaptation of those additional data, a more universal network would be obtained. The upgraded network might be capable to predict heating demand for a larger group of single-family houses in terms of their geometry parameters.

The last validation of the trained network was performed for two different heating system types. In the performed analyses, a traditional system with the heating stove and a modern one with the GHP application were defined. For the traditional system, a range of stove COP values have been used (from 0.59 up to 0.87, varied by 0.04), while for the GHP applications of only 2 different values (out of producers' brochures) were considered.

A)



B)



C)

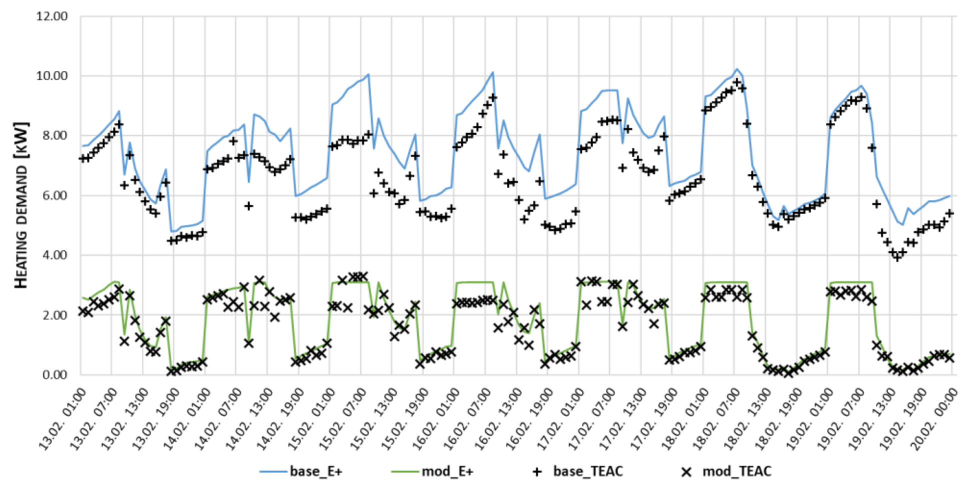
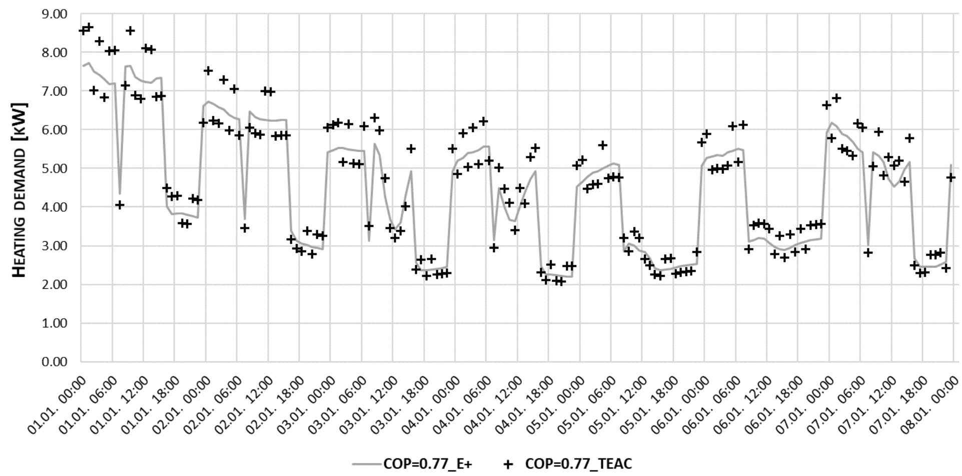


Figure 3.17. *Comparison of time distribution values of heating demand obtained by means of the Energy Plus and the defined network for* ***A****) Czestochowa;* ***B****) Gorzow Wielkopolski and* ***C****) Olsztyn*

Some exemplary heating demand predictions are presented in **Figure 3.18**. The graph shows the heating demand time distributions for RSFH_3 located in Lodz, for the traditional heating systems with COPs of 0.77 and 0.87 at the base variant of building enclosure, obtained by means of the *Energy Plus* and *TEAC* softwares. The COP equal to 0.77 is out of the dataset used during NN training process, nevertheless, a sufficient accuracy was obtained. For an exemplary period of single week (from 1st to 7th January) the accuracy of 1.024 and 0.964 was obtained accordingly for the analysed scenarios of heating systems with COPs 0.77 and 0.87. For the whole year prediction, the total heating demand accuracy of 1.049 and 0.955 was obtained.

It might be concluded, that for the defined range of COP values of traditional heating systems the network is an appropriate tool for heating demand predictions. On the other hand, only 2 different values of GHPs COPs are not enough in order to obtain accurate predictions for values different than predefined ones. Summarizing, the actual NN is capable to predict heating demand for Polish representative single-family houses with a traditional heating system, which efficiency is within the analysed range of COPs. Unfortunately, for the GHP application predictions performed by the network are valid only for predefined scenarios.

A)



B)

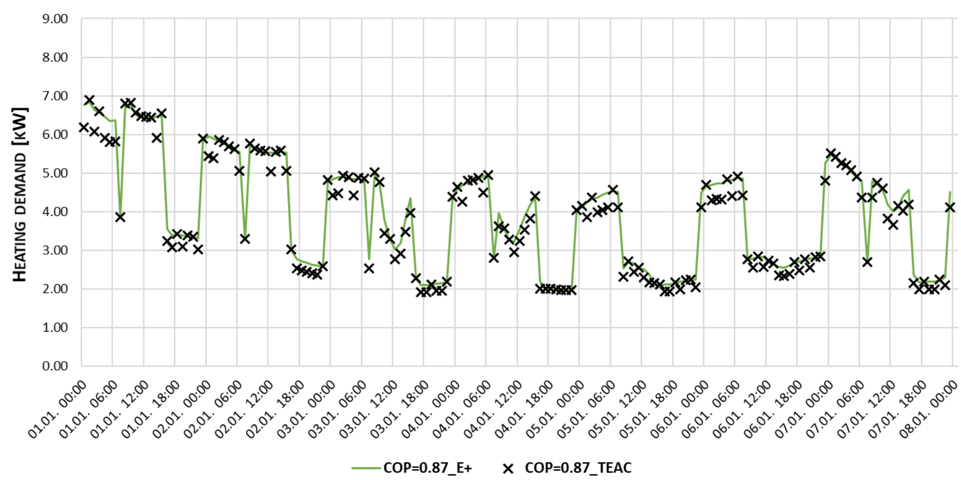


Figure 3.18. *Comparison of the time-distribution of heating demand obtained by means of the Energy Plus and the defined network for different COPs of DH systems:* ***A****) COP=0.77 and* ***B****) COP=0.87*

3.7.3. RESULTS MODULE – AVAILABLE OUTPUTS

In the results module, we need to select on what type of outputs we are interested in. There are two groups of results in the *TEAC* software. In total, in the results module there are seven submodules, each of them operates one type of outputs. The first group includes all the default results, which are generated automatically, whenever the analysis is performed. There are three submodules in the first group of results. By default, heating and electricity LDCs, area mappings and energy consumptions data are summarized. Considering the area mappings, data on heating and electricity consumption distribution are shown. The default results are presented for the exemplary studies in sections **3.8** and for all the cases in chapter **4**.

The second group concerns optional results – the user can decide if use it or not. There are four submodules in this group. The first two of them allow to perform RES analyses for solar or wind energy applications – they are described accordingly in subsections **3.7.4** and **3.7.5**. RES (both solar and wind) potential is presented in electricity LDCs, as well as in energy consumptions data. Additionally, for PV systems, it is possible to include the obtained outputs in the electricity consumption map for the analysed area. The third submodule might perform cost-effectiveness analyses of the proposed modernizations – the applied procedure is presented in subsection **3.7.6**. As the default output of this submodule, a summary table is received. It is also possible to obtain graphs of financial profitability in time for the NPV and LCC methods. The last submodule of optional results is related to ecological analyses concerning greenhouse-gasses emissions (see subsection **3.7.7**), CO_2, SO_2 and NO_x, as well as $PM_{2.5}$ and PM_{10}. The emissions results are presented by means of maps and summary tables.

In the *TEAC* software selection of the additional outputs in which we are interested in is simple. All what is needed is to prepare a new input **.csv* file (describing the investigated problem) and then run the appropriate submodule. The format of those new input files vary depending on the type of analysis. The *TEAC* software creates output **.csv* files, out of the data typed in the module 1(area description) and module 2 (application of ANN). The module 3 uses those files as well as a new input file to calculate required outputs. Again, the outputs from module 3 are also saved as **.csv* files – all of the obtained files can be manually modified. Therefore, in order to receive results, which fully satisfy the user it is required to perform some data analyses, based on the obtained results.

In order to present more detailed introduction to the *TEAC* software, the two basic variants of BCs are shown in section **3.8**. Thanks to the performed analyses of small building areas, it is possible to present most of the *TEAC* software features – the bigger analysed area is, the more complex analysis is performed.

3.7.4. SOLAR ENERGY SUBMODULE

In this submodule the analysis concerning RES application for solar energy is possible. Solar energy is assumed to be used by means of PV panels. The calculations are made apart of the NN module, based on geometry data of buildings' roof and the solar irradiation data of the analysed localization. For the solar energy calculations, the *TEAC* software is using the output **.csv* files in order to use the irradiation data (from the module 2) as well as the available roofs areas, their orientations and inclinations (from the module 1). There are two additional steps which are required to perform the solar energy calculations for the defined BC, using the *TEAC* software.

The first one related to the selection of buildings for further analyses of solar energy applications. It is possible to select all the buildings within analysed BC, or manually input the coordinates of selected buildings (each one separated with a comma). It is possible to make a mistake and input the coordinates of an empty parcel – then, due to the lack of available roof area on the selected cell, the obtained result for that particular parcel will be equal to zero. The above-mentioned possibility is not affecting solar energy outputs obtained for the whole BC. Nevertheless, whenever coordinates for the wrong building is used, then the obtained results will be affected by the error. The method of input data preparation (with the building selection) for calculations of solar energy usage is presented in the example no. 1 (see subsection **3.8.1**) in **Appendix 7**. The solar outputs are calculated based on building types as well as their placements and orientations.

The second required step is input of the technical parameters of applied PVs. There are three necessary attributes, which are needed to define PV, its' length (L_{PV}) and width (B_{PV}) as well as its efficiency (η_{PV}). It is possible to define those parameters fully manually, *i.e.* building by building, nevertheless, it is time-consuming and considered as a not-recommended approach. The recommended way is to use the keyword '*all*' and after that define the size and efficiency of the used PV panel model only once, for all buildings consisting the analysed BC. The author is aware, that the proposed method might not represent the actual state of the PV installation systems – the applied solutions might vary for each building within the analysed BC. Nevertheless, the calculations are made to show the potential for solar energy usage in the analysed area – therefore the standardisation of the all PV installations is assumed. Besides, the differences in efficiency of the up-to-date models of PV panels are marginal, just as in their sizes. Therefore, it is possible to define parameters of the applied PV panel model using another keyword '*standard*'. If so, data for an average PV panel in 2018, according to the records published in [81], [299], will be used. Based on the report, the representative PV panel in 2018 has an efficiency of 18.85 %, 1.65 m long and 1.00 m wide (it consist of 60 solar cells). Of course, it is possible to define any commercially available PV panel model.

There are several assumptions set in order to define a profitable placement of PV panels. Whenever roof surface is oriented North, North-East or North-West PV application on these surfaces is aimless. Also, an appropriate placement of PV panels on available roof area is considered, by means of panel size, not only a total area of the arrangement – the schema of panels placement can be seen in **Figure 3.19**. The solar module firstly examines the available roof area (depending on the building type) in terms of appropriate selection of PVs number. Then, using PV's length and width, the maximal number of panels is calculated, horizontally and vertically. Horizontally it is limited with $b_{PV,min}$, which is at least 0.50m from the roof edges

– the panels are centralized, that the side-plane is the same on both edges. Vertically, the panels are always placed 0.50m ($l_{PV,min}$) from the lower edge of the roof. The remaining length is denoted as l_{left}. The mentioned approach allows avoiding overestimation of the total PV installation area (the total available roof area is larger, but it is unattainable technically).

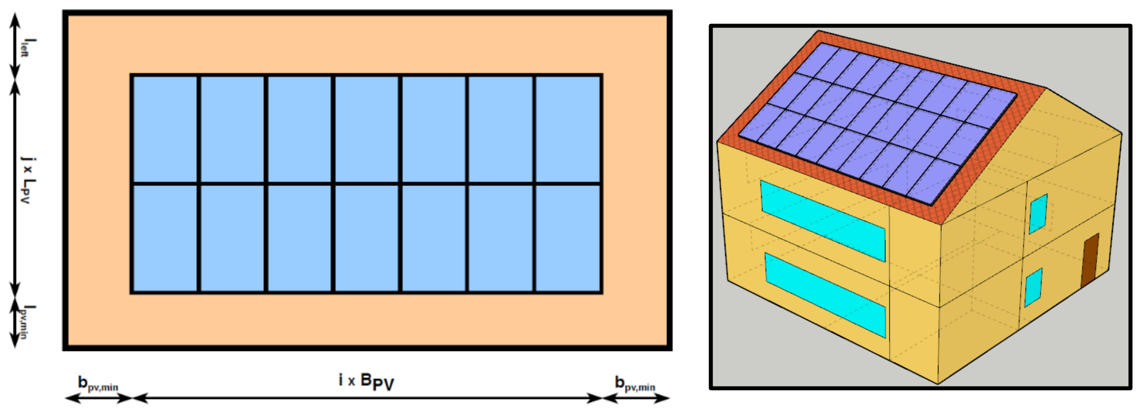


Figure 3.19. *Schema of used PVs placements on available roof area (on left) and visualization of building with PV installation (on right)*

Besides, calculations of PVs application are performed for a single year period. Therefore, losses in system efficiency, that occur due to exploitation (wear) of the system are neglected. In order to include the effect of system age user might input efficiency which will include the impact of its' exploitation. Nevertheless, in the present version of the *TEAC* software, it is not possible to perform solar energy calculations, including aging of PV systems.

The method used here for calculation of solar energy outputs is frequently applied for those types of assessments. The **I**sotropic **R**adiation **M**odel (IRM) was used – it is comprehensively presented in the book written by *Chwieduk* [2]. The IRM was proposed in 1942 by *Hottel* and *Woertz* [109]. The proposed model was later improved in 1963 [158] by taking into account the hemispheric radiation incident on a tiled surface. The hourly solar irradiation (I_c) of a tilted surface consists of three components (see **Figure 3.20**), accordingly the beam radiation, diffuse radiation and radiation reflected by surroundings, and it is described by equation (2.7). The equation includes the correction factors for beam (R_b), diffuse (R_d) and reflected (R_r) radiations, as well as surface reflectance (ρ_o).

$$I_c(t) = I_b(t) \cdot R_b(t) + I_d(t) \cdot R_d + \left(I_b(t) + I_d(t)\right) \cdot \rho_o \cdot R_r \tag{2.7}$$

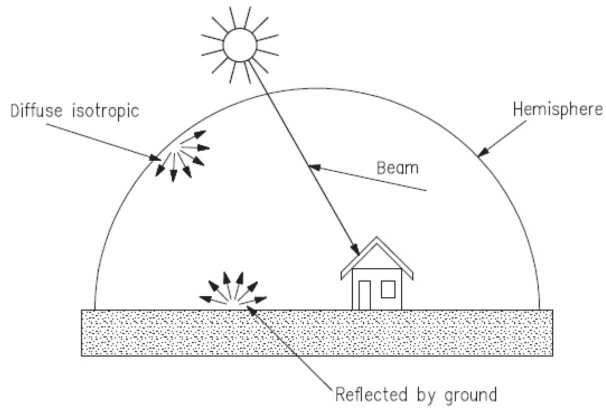


Figure 3.20. *Schematic diagram of the IRM (source: [2])*

The correction factors for diffuse and reflected radiations are quite simple to estimate and are based on the relationship between the angled irradiated surface and the horizontal plane. The correction factor for beam radiation is expressed by equation (2.8). It can be described using a complex function of the latitude (φ), tilt angle (β), azimuth angle (γ), declination (δ) and solar angle (ω). The key relations used during potential solar outputs are presented in **Figure 3.21**. The hourly data from TMR files are used for solar energy calculations.

$$R_b(t) = f\left(\varphi, \beta, \gamma, \delta(t), \omega(t)\right) \tag{2.8}$$

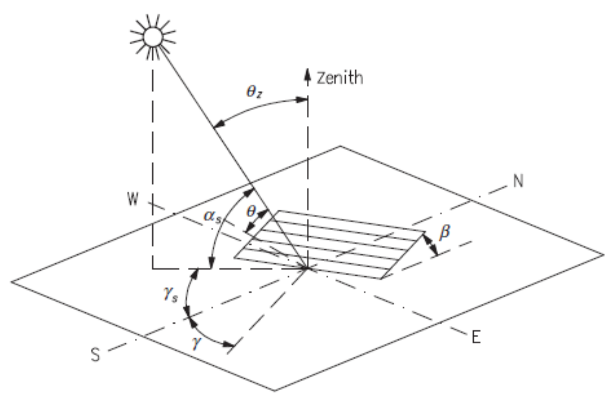


Figure 3.21. *Key relations between the Sun's position and a tilted irradiated surface (source: [2])*

Shading influences potential solar energy usage significantly – therefore it is crucial to design those type of systems avoiding or at least minimizing the shading impact. All nearby obstructions which might generate shadow on the applied solar system need to be taken into account. Obviously, obstacles located to the north of the array are of no concern (because of the sun-path during the day). Additionally, during shading impact analyses the common and frequently used practice is to examine shading that occurs only during the so-called **S**olar **W**indow (SW). SW occur from 9 AM till 3 PM, when solar irradiation is the highest. Nevertheless, it is a common practice to extend the SW time span during the summer months. Below, the applied procedure used in the *TEAC* software for shading impact analysis is presented.

The shading impact study is performed for SW time span, with some modifications, assumed in order to maximize the solar energy usage. For January, February, March, October, November and December a standard SW period is assumed (9 AM – 3 PM). For April, May and September the time-gap is extended from 8 AM till 4 PM. And finally, for the summer months (June, July and August) SW time span is assumed from 6 AM till 4 PM. A comparison of the total solar irradiation with that occurring during SW (with the above-mentioned assumptions) for the all analysed localizations is presented in **Table 3.13**. It can be seen, that the solar irradiation during the selected hours consists, by average, of approx. 88 % of the total irradiation for the all analysed localizations. It is concluded, that the shading impact analyses for the defined SW are valid for proper solar systems applications and exploitations. During the potential solar outputs calculations some losses which are typically existing within the PV systems (*e.g*. an efficiency decrease occurring on inverter) are not considered. Nevertheless, it can be assumed, that the lower solar irradiation (during SW time) used for calculations considers in some way the neglected losses of the system. All the solar energy calculations performed by means of the *TEAC* software are made using the defined SW.

Table 3.13. *The comparison solar irradiation – whole year vs SW time*

LOCATION	TOTAL.	SW TIME	DIFF.
	[kWh/m^2]		[%]
GDANSK	886.36	792.12	**89.37**
LEBA	847.39	767.15	**90.53**
SZCZECIN	863.00	771.71	**89.42**
PILA	902.50	799.74	**88.61**
WROCLAW	992.87	869.09	**87.53**
LODZ	978.50	849.48	**86.81**
WARSAW	977.93	851.31	**87.05**
BIALYSTOK	897.14	778.09	**86.73**
CRACOW	1045.54	897.36	**85.83**
RZESZOW	1051.34	892.86	**84.93**

As it was already said, the solar systems should be designed in order to avoid shading during the SW time span. For all the analysed cases, the shading impact is included in total electricity production out of the PV systems. The performed analyses are based on the sun positioning, or more precisely on its elevation, obtained from the sun-path charts for the considered localizations. The worst-case scenario is observed during a winter solstice – the lowest elevation of sun, accordingly 21st December at 9 AM (first hour of the SW). In other words, if the solar system is not shaded during the winter solstice, it will not be during the whole year – it is the best possible design.

In the performed study, for all the analysed scenarios of nearby obstacles have always the same size – it is a square-based block 11x11m (a_{SB}), 8 m tall (h_{SB}). The obstacles are always positioned directly in the centre of each parcel, and they are generating the most disadvantaging conditions relating to potential shadings (the predefined blocks are larger than the biggest model of the considered building types). The sun path charts for all the considered localizations are used in order to obtain the elevation of the sun at the given time. Whenever the user defines climate conditions by himself, the Lodz sun path chart is used in order to calculate the solar energy outputs; Lodz is located in the geographical centre of Poland, thus the obtained results can be considered as the national average. The shading impact is analysed for all 365 days of the year, for the extended SW time span. It was assumed, that if shade reaches the building roof, there is no energy production out of applied PV system for that particular hour. The used method is based on the trigonometric calculations considering the sun positioning, obstacles size and distance between each obstruction and the analysed building.

Firstly, shading based on the solar positioning at the given time is calculated – from the sun path chart the elevation of the sun up above the horizon (attitude angle) is readout. Therefore, using the attitude angle (α) and knowing the obstacle height (h_{SB}) we can calculate the first shading length (Y_{SH}) as shown in **Figure 3.22**. Equation (2.9) was used in order to calculate Y_{SH} at a given time.

$$Y_{SH} = {h_{SB}}/{\tan(\alpha)} \tag{2.9}$$

Secondly, shading based on the solar azimuth angle is calculated – it is again obtained from the sun path chart for the given time. The performed calculations are based on the already obtained Y_{SH}, as well as the β' angle, which is a difference between 90 degrees and the solar azimuth angle (γ) at the given time. As a result, the second shading length (X_{SH}) is obtained – it can be seen in **Figure 3.22**. Equation (2.10) is used in order to calculate X_{SH} at the given time. It can be also expressed more comprehensively, as shown in equation (2.11).

$$X_{SH} = \sin(\beta') \cdot Y_{SH} \tag{2.10}$$

$$X_{SH} = \frac{\sin(\beta')}{\tan(\alpha)} \cdot h_{SB} \tag{2.11}$$

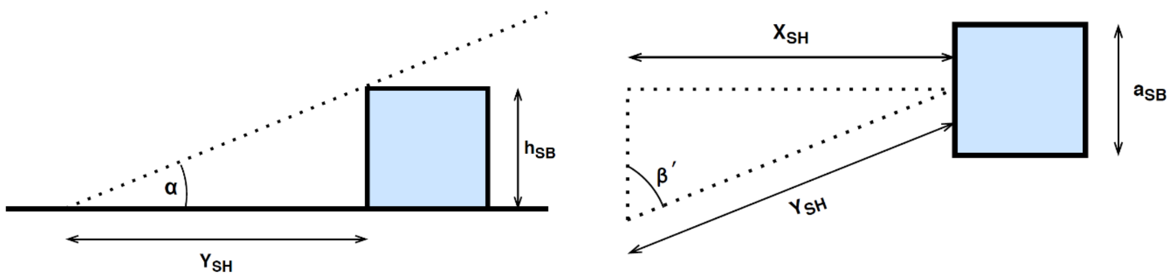


Figure 3.22. *Schema of shading calculations: vertical view – solar attitude angle impact (on left); horizontal view – solar azimuth impact (on right)*

The both shading lengths (X_{SH} and Y_{SH}) are shown in **Figure 3.23** to illustrate an exemplary scenario. If X_{SH} is greater than the distance between the building and an obstacle (X_D), the solar outputs are equal to zero for this given hour. X_D is easy to calculate because both the building and obstacle positioning on each parcel is known. The mentioned analysis is performed for all obstacles in East, South or West from the analysed building. Obstructions such as trees or natural hills are not included in the *TEAC* software.

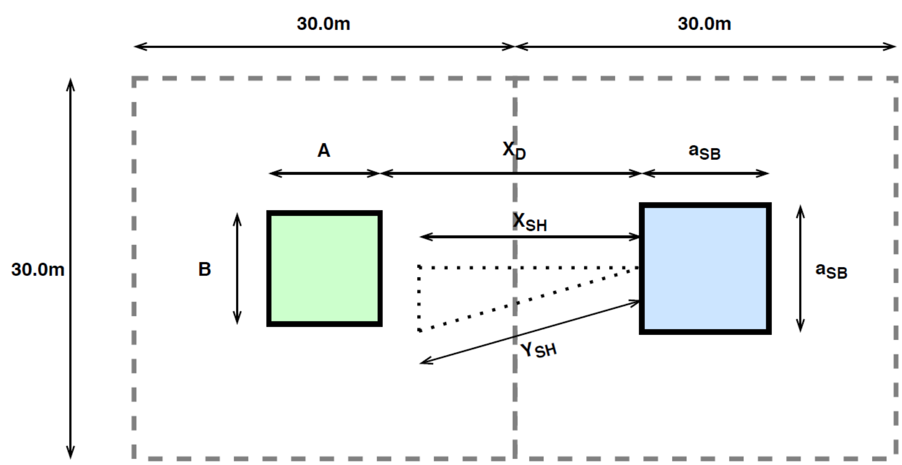


Figure 3.23. *Schema of shading assumption method used in the solar module in the TEAC software*

Summarizing, a short guideline for proper PVs placements (avoid shading) consists the following steps:

- generate a sun-path diagram for the analysed localization (latitude, φ),
- determine the azimuth angle (γ) and size of nearby obstructions,
- calculate or measure the attitude angle (α) of nearby obstructions,
- analyse the data to determine shading impact.

There are numerous remedies to correct or mitigate the problem of shading occurring on the solar installation. Whenever it is possible, it is recommended to move the array in order to avoid shading from nearby obstructions. The simplest reallocation of the solar system is performed by rising the array's height – it results in lowering the obstacle altitude angle. Moreover, a non-rectangular configuration of PVs array is often a more efficient approach of panels placement. Additionally, various technologically advanced tracking systems can be applied instead of fixed montage of PVs.

There are several available options for presentation of outputs concerning solar energy application in the *TEAC* software. Whenever solar energy is considered, the *TEAC* software generates a data file with the hourly values of electricity production out of the applied PV systems. The obtained data might be included in the electricity maps of the analysed area, as well as in its electricity LDC. Additionally, the obtained hourly distributed amounts of produced electricity can be compared with the electricity loads for the analysed area (or for singular or group of buildings). Moreover, it is possible to obtain the comparison of how electricity is shared between the '*on-grid*' solar systems. The obtained comparison includes the amount of electricity produced, used instantly, sold to the grid as well as received back from the grid. The received amount of electricity is divided dependent on given electricity consumption. Finally, the obtained data can be used in a summary for the analysed BCs. Some results obtained using the solar energy module of the *TEAC* software are presented in chapter **4**.

3.7.5. WIND ENERGY SUBMODULE

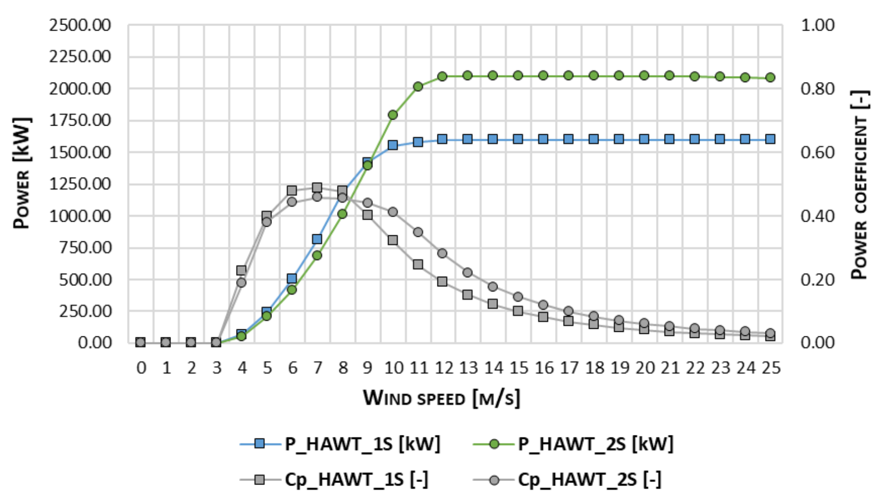
There are several assumptions in the wind-energy submodule. Firstly, the wind energy potential can be analysed in two major scenarios: as onshore or offshore setup. The offshore situation is available only for localization close to the seaside – in the *TEAC* software, these are Gdansk, Leba and Szczecin. For all the remaining seven pre-defined localizations only onshore analyses are available. If localization is defined by the user, through input climate conditions, the offshore analysis is always available. It is important to mention, that the offshore wind energy potential analysis is performed for the wind conditions measured at the *FINO 2* research platform [383] – therefore the obtained results are always the same, no matter what localization has been selected. Additionally, the wind energy analysis can be performed for both HAWT and VAWT systems. Whenever option with the VAWT is selected, it is assumed, that for each building only one turbine is applied – therefore the maximal number of VAWT is equal to a number of buildings consisting the analysed area. When the HAWT option is selected, it is necessary to define number of turbines. It is assumed, that local **W**ind **T**urbines **F**arm (WTF) consists of turbines of the same type. Additionally, electricity losses occurring from distribution are neglected. The positioning of HAWT is selected to maximize the potential electricity outputs out of the wind. The selection is based on the typical wind directions, predefined for each localization (see **Figure 3.5**). Wind blowing from directions perpendicular to the turbine front is not included in the calculations. The *TEAC* software has the built-in database of several commercially available wind turbines, accordingly two onshore HAWT, the two offshore HAWT and two VAWT. Their technical parameters can be seen in **Table 3.14**. Additionally, in **Figure 3.24** we can see the comparison of power curves for each turbine.

Table 3.14. *Technical parameters of the wind turbines from the TEAC software database (source: [401])*

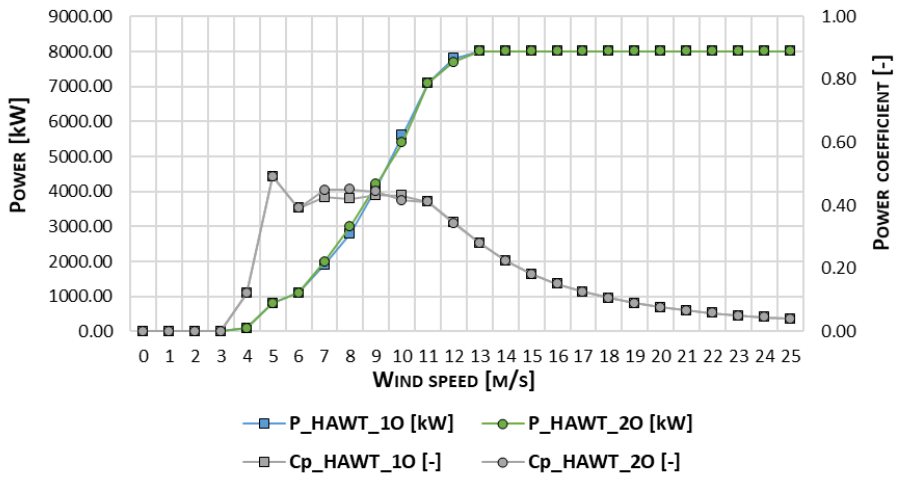
PARAMETER	HAWT_1S	HAWT_2S	HAWT_1O	HAWT_2O	VAWT_1	VAWT_2
PRODUCER	*GE*	*SUZLON*	*AERODYN*	*VESTAS*	*HIVAWT*	*HIVAWT*
MODEL	1.6-100	S95-2.1	SCD8.0/168	V164-8.0	DS1500	DS-3000W
TYPE	H	H	H	H	V	V
APPLICATION	ONSHORE	ONSHORE	OFFSHORE	OFFSHORE	ONSHORE	ONSHORE
P_{max} [kW]	1 600.00	2 100.00	8 000.00	8 000.00	1.50	3.00
h_H [m]	100.00	100.00	100.00	102.00	4.00	8.20
d_R [m]	100.00	95.00	168.00	164.00	2.94	4.00
h_R [m]	N/A	N/A	N/A	N/A	2.80	4.20
A_{SA} [m^2]	7 854.00	7 084.00	22 167.00	21 124.00	8.23	16.80
V_{C-I} [m/s]	3.50	3.50	3.50	4.00	3.00	3.00
V_R [m/s]	11.00	11.00	11.50	13.00	12.00	12.00
V_{C-O} [m/s]	25.00	25.00	25.00	25.00	15.00	15.00
V_S [m/s]	N/D	59.50	50.00	50.00	60.00	60.00

Where: P_{max} – rated power; h_H – hub height; d_R – rotor diameter; h_R – rotor height; A_{SA} – swept area; V_{C-I} – cut-in wind speed; V_R – rated wind speed; V_{C-O} – cut-off wind speed; V_s – survival wind speed

A)



B)



C)

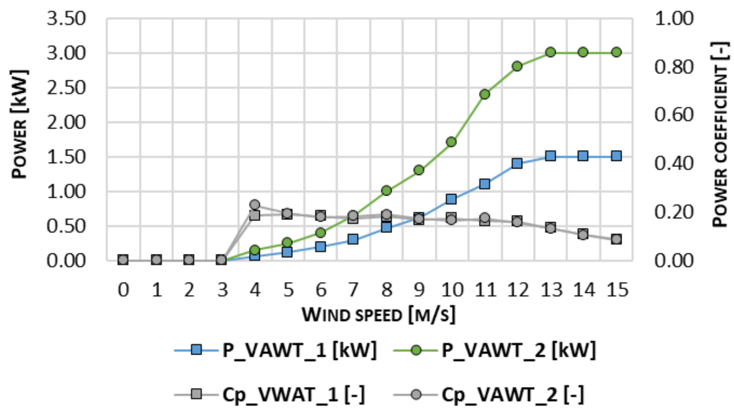


Figure 3.24. *Power curve for wind turbines from the TEAC software database, accordingly:* **A)** *onshore HAWT;* **B)** *offshore HAWT and* **C)** *VAWT (source: [401])*

It is possible to define a new type of wind turbine by the user. Therefore, it is necessary to input the obligatory parameters of the selected turbine. The set of required data includes as many lines, as the value of cut-off speed is, including the following parameters: turbine type, hub height (h_H), rotor diameter (d_R), rotor height (h_R), available power at a given wind speed (P_i) and power coefficient at a given wind speed ($C_{P,i}$); each parameter should be separate with a comma. The exemplary definition of a wind turbine for the *TEAC* software application is presented below (as an example, the HAWT_1S was used). The new turbine is saved as a '*H_AWT*' or '*V_AWT*', dependent on the defined type.

{H, 100.00, 100.00, n/a, 0.00, 0.0000};

{H, 100.00, 100.00, n/a, 0.00, 0.0000};

{H, 100.00, 100.00, n/a, 0.00, 0.0000};

…;

{H, 100.00, 100.00, n/a, 1600.00, 0.0272};

{H, 100.00, 100.00, n/a, 1600.00, 0.0240};

{H, 100.00, 100.00, n/a, 1600.00, 0.0212}

Whenever we are interested in wind energy application into the analysed area we need to open the wind energy module and simply select type of the applied wind turbine. This is performed using symbols (such as HAWT_1S). Whenever the user selects a horizontal turbine, their number is also required to be defined. If the vertical turbine is selected, the *TEAC* software requires also buildings selection, for which they will be applied. The selection can be performed automatic, for all the buildings in the analysed area (it is done with the keyword '*all*') or manually, using buildings' coordinate (X_i_Y_i).

The wind energy submodule calculates the hourly electricity production following the simple method presented in [1], [10]. The amount of obtained electricity is based on the wind conditions, as well as the applied turbines parameters. Additionally, the applied method includes the impact of wind speed at a given height (not at the measured level), expressed with equation (2.6). The obtained electricity out-of-wind usage is calculated using the following equation.

$$P_{avail} = \frac{1}{2} \cdot \rho \cdot A_{SA} \cdot V_h^3 \cdot C_P \tag{2.12}$$

The obtained results might be included in electricity LDC of the analysed BC. Additionally, potential electricity produced out of wind might be presented at load time-distribution graphs. Moreover, the amount of produced energy might be included in the emissions' calculation. Finally, the amount of produced electricity can be included in the analysed area summary.

3.7.6. ECONOMIC SUBMODULE

In the *TEAC* software three methods of economic assessments are implemented, accordingly SPBT, NPV and LCC. All the applied methodologies are introduced in subsection **2.5.1**. In order to perform economic analyses of buildings' modernizations by means of the *TEAC* software, the appropriate set of outputted *csv*-type files are required. Those files are generated in the previously described modules of the code. Those files contain information related to the analysed area, for scenarios before and after proposed modernizations (predefined in module 2) as well as the files with base results output from module 3.

The first pair of files is used for modernizations' cost calculations. The files are compared in order to receive information on what modernizations were performed. Then, the module uses the built-in data set with the modernizations' cost to estimate the endured expenses. The analysis is performed '*building by building*', therefore it is possible to obtain an economic assessment for a single object, as well as for a part-of or the whole analysed area. The cost of each modernization is defined based on the data published in the specialist buildings' estimated budgets called '*Biuletyn*', published by the ***O****środek* ***W****drożeń* ***E****konomiczno-***O****rganizacyjnych* ***B****udownictwa* (OWEOB). In those reports, all the costs related to single-family houses (but also for other building types) modernizations, valid in Poland, are included. Each price is divided into the materials and labour costs; the materials costs are assumed from the actual producer's offer, while the labour costs are estimated based on the *Biuletyn* for the second quarter of 2019. All the buildings renovation costs can be freely changed, whenever it is needed.

The second pair of files is used for estimating the annual savings based on a reduction in the amount of consumed energy. Those savings are a basis for economic profitability analyses. With the given energy consumption reduction, it is possible to estimate the annual savings for each building of the analysed BC. The annual savings are obtained using the fuel prices; the electricity cost is assumed as the national average (beginning of 2020) while the cost of locally used fuels such as coal or gas is taken from the actual price-lists. Same as with the modernization costs, the energy-related costs can be easily updated.

The above-introduced information is used to perform an economic analysis for the analysed BC. It is necessary to define, in what type of analysis we are interested in. Therefore, building selection, as well as the applied method is necessary to outline. The economic analysis can be performed for a single, several or all buildings consisting of the analysed area. It can be performed for the whole area using the keyword '*all*' or manually – then it is necessary to select the appropriate buildings using their coordinates. Similarly as it is in the solar energy submodule (see subsection **3.7.4**) it is possible to make a mistake and to input coordinates of an empty parcel – then, the result obtained from an economic analysis will be equal to zero. But, whenever coordinates for the wrong building will be used, then obtained outputs will include the error. Finally, we need to select, which economic method should be used for the purpose of our analysis. The available methods are in order, as follows: SPBT, NPV, LCC; the selection is performed by typing '*1*', otherwise, we should input '*0*'. It is necessary to do a selection for the all available methods, separated with commas. It is recommended to perform economic analyses for the whole BCs – it is always possible to find outputs for a single building in outputted *csv*-files. The schema on how to define the economic analysis is presented below.

{*building selection*, SPBT, NPV, LCC}

While an exemplary definition might be as follows:

{*all*, 1, 1, 1}

Several ways of economic outputs are available in the *TEAC* software. Those outputs can be obtained for a single building or as averages for each building type or the whole analysed area. Considering the SPBT method, the value in years is obtained – it can be used to generate profitability map for the analysed area, or summarized in table form. For NPV or LCC analyses two types of outputs are possible: in graph form or with values. As a value-based result, the total cost of each building usage after an analysed period of time (usually 30 years) can be obtained. Moreover, NPV_0 and LCC_0 values are available – those values inform when the performed modernization starts payoff. Again, using the above-mentioned values it is possible to perform profitability maps, as well as summarize results in table form. Available graphs show time-distribution costs after the considered modernizations in comparison with the base scenario.

Some exemplary applications of the economic submodule are presented in section **3.8** as well as in chapter **4**.

3.7.7. ENVIRONMENTAL SUBMODULE – EMISSIONS ASSESSMENT

Environmental analyses performed by means of the *TEAC* software are based on harmful gasses emissions from burned fuels, used in energy production. Those types of analyses are extremely important in terms of countering the smog and improving air quality. They are particularly essential for Poland due to the numerous alerts of poor air-quality, announced by specialized institute such as EEA [382].

Out of GHG, CO_2, SO_2 and NO_x compounds, as well as $PM_{2.5}$ and PM_{10} were selected because they are the most common and hazardous ones. Calculations were made based on emissions data, published in report performed by the *National Centre for Emissions Management* (in Polish: ***K**rajowy **O**srodek **B**ilansowania **i** **Z**arzadzania **E**nergiami*, KOBiZE) [314]. The document includes a mass amount of gasses, produced during the energy production process or more precisely during combustion. Hence, calculations performed by this module are very simple, nevertheless, it requires several assumptions to be made. The first step is the preparation of data with energy consumption by each building and a supply fuel type used for heat production. Those data are already defined in previous modules of the *TEAC* software – the amount of consumed energy for heating purposes is predicted (output in module 2) while used fuel type is predefined in building data, based on selected modernization variant. Emissions occur from electricity production are a result of processes performed in national power plants. Therefore, supply fuels were assumed using shares valid for electricity production in Poland (see **Figure 2.7** and **Figure 2.8** in section **2.2**). According to predictions for 2020, the share of supply fuels in Poland is as follows: 43.5 % hard coal, 30.5 % brown coal, 6.7 % gas and 19.3 % RES. The general equation used to estimate the amount of emissions is presented below.

$$E = B_F \cdot w_F \qquad (2.13)$$

All what is necessary to perform those type of estimations for heating energy is a database with emissions factors values for different substances (w_F) and method to convert the amount of consumed energy to amount of used fuels (B_F). Based on the consumption and fuel **N**et **C**alorific **V**alue (NCV) it is possible to estimate the required mass (or volume) of the fuel. Thus, the equation (2.13) can be substituted with more complex form, as presented below.

$$E = H_c \cdot NCV \cdot w_F \tag{2.14}$$

Estimating emissions from electricity production process it is a more complex venture, due to the necessity of converting heat into electricity. For the purposes of performed analyses, it was assumed, that electricity came from national power plants, except the amount generated by housing systems of RES applications. The process of converting heat into electricity is characterized by low efficiency. Presently used power units in Poland are old-fashioned and their efficiency is much lower than currently available units. Power plants supplied with coal (both hard and brown) have power units with efficiency approx. 36 %, while the highest technologically-advanced systems are capable to convert up to 60 % of heat. National power plants of Poland, supplied with gas have more efficient power units – their efficiency is approx. 44 %, while presently available, the most advanced ones', reach an efficiency of 67 %. Therefore, for emissions calculations, the amount of electricity consumed by the analysed BC is converted into the required amount of heating energy, used by the national power system. The applied procedure has a logic schema. In the beginning, the amount of consumed electricity for each building constituting BC is calculated. Then, if RES are applied the available amount of produced electricity (dependent on time-demand – see more in subsections **3.7.4** and **3.7.5**) is deducted from buildings' consumptions. Next, the remaining amount of electricity is converted into heating energy, using fuel shares in Polish national electricity system – efficiencies of power units are used. It was assumed, that electricity produced out of RES (locally and by the national system) is characterized with no emissions. Finally, the amount of emissions is calculated, based on w_F values for different fuels. Additionally, obtained values of emissions are multiply by factor expressing losses during electricity distribution – according to data published by the *National Security Bureau of Poland* (in Polish: ***B**iuro **B**ezpieczenstwa **N**arodowego,* BBN) [417], it is approx. 7 %. The equation (2.15) presents the applied method used for emissions estimation of given electricity consumption (where *i* represents different fuels types).

$$E = k_D \cdot (E_C - E_{RES}) \cdot \sum k_{S,i} \cdot \frac{w_{F,i}}{\eta_{PU,i}} \tag{2.15}$$

In **Table 3.15**, values of NCV and average w_F for different fuel types are presented. These are all possible fuels used in the performed study. In this module, default results are presented by means of CO_2 emissions maps for the analysed BC. CO_2 emissions were selected because they are the most common and the most representative from all GHG – therefore those results can be used to assuming a range of other emissions in the analysed area. As usual, in generated maps each cell represents one building, constituting the examined BC. Nevertheless, complete emissions data (for the whole analysed area) is obtained in table form, as a sum of emission for each gas. The most efficient approach of emissions results is by comparison of scenarios before and after modernization. More environmental module applications can be found in section **3.8** and chapter **4**.

Table 3.15. *Net Caloric Values (NCV) and emissions factors (w_F) for different fuels (source: [314])*

FUEL	EMISSIONS (w_F) [g/kWh]					NCV
	CO_2	SO_2	NO_x	$PM_{2.5}$	PM_{10}	
BROWN COAL	565.35	$4.75 \cdot s_1$	0.46	1.52	1.96	14.20* [MJ/kg]
HARD COAL	309.50	$2.61 \cdot s_1$	0.26	1.19	1.54	22.10 [MJ/kg]
GAS	280.92	$3 \cdot 10^{-4} \cdot s_2$	0.25	0.05	0.05	25.63 [MJ/m^3]
PELLET	276.92	0.03	0.22	0.31	0.45	15.60 [MJ/kg]
ELECTRICITY (BROWN COAL)	398.73	$3.35 \cdot s_1$	0.33	0.76	0.98	16.65 [MJ/kg]
ELECTRICITY (HARD COAL)	343.73	$2.89 \cdot s_1$	0.29	0.59	0.77	24.30 [MJ/kg]
ELECTRICITY (GAS)	201.96	$2 \cdot 10^{-4} \cdot s_2$	0.18	0.03	0.03	36.20 [MJ/m^3]
ELECTRICITY (NATIONAL)	285.01	5.21	0.24	0.49	0.64	N/A

Where: s_1 – the content of sulphur, expressed in %; s_2 – the content of sulphur, expressed in mg/m^3; * - average value from a given range

3.8. PRELIMINARY EXAMPLES OF THE *TEAC* SOFTWARE APPLICATIONS

In this section, two simple examples of BCs were analysed using the *TEAC* software. The presented examples concern 4 (subsection **3.8.1**) and 27 (subsection **3.8.2**) single-family houses. Most of possible results obtained by means of the *TEAC* software are shown in the following subsections. The step-by-step procedure on how to perform those examinations is presented in **Appendix 7**; this section is focused on results showcase only.

3.8.1. EXAMPLE NO. 1 – 2X2

The simplest possible analysis performed using the *TEAC* software concerns just one building. Nevertheless, whenever we are focused on USEM analyses, at least several buildings should be considered. Therefore, the first example of the *TEAC* software application is shown for some exemplary BC consists of just 4 SFHs. For the purpose of the presentation, the analysed area is a square-shaped BC, 2x2 parcels, with one of each buildings type, accordingly, RSFH_1, RSFH_3, RSFH_5 and RSFH_7 – the 3D visualization of the analysed area can be seen in **Figure 3.25**. The analysed BC was defined manually, using the **DT1** method from the *TEAC* software (see more in subsection **3.7.1**). As usual, whenever the *TEAC* software is used, each building parcel is a cell 30x30 meters, with a building located directly in its' centre. The considered BC is located in Lodz. The procedure expressing how to define the analysed area by means of the *TEAC* software is shown in section **A.7.1**. Additionally, some additional results presented by means of maps are shown in the above-mentioned section (**Appendix 7**).

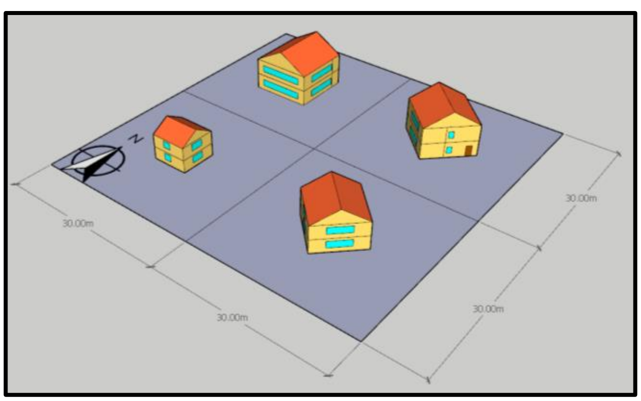


Figure 3.25. *Visualization of the analysed area consists of 4 buildings (BC 2x2; example no. 1)*

In this scenario, three modernization variants are considered. The first one demonstrates the base variant (assigned as **V0**), the second one (assigned as **V1**) assumes buildings enclose modernization following the 2021 requirements, while the third one (**V2**) includes heating system upgrade simultaneously with the **V1** variant. Additionally, lighting systems modernization is considered, as well as RES (solar energy) applications. For such a small residential area an application of wind turbines is rather aimless – the usage of wind energy is not included in this example.

By default, the examined BC is analysed by means of maps and LDCs. The set of the output maps, for scenarios before and after modernization, is presented in **Figure 3.26**. The first maps arrangement represents a comparison of the annual energy consumption for heating purposes (variants **V0** and **V2**), while the second one presents the electricity consumption for base scenario and with LEDs application (assign as **V3**). The base LDCs (without RES usage) are presented in **Figure 3.27**; a collation of heating and electricity LDCs for some of the considered variants can be seen. Additionally, the obtained data can be furtherly used. A summary of the energy consumption by the analysed BC can be found in **Table 3.19**. The proposed thermal-renovations result in lowering the heating consumption by 64 640.18 kWh/a (69.34 %) for the **V1** scenario and 68 243.17 kWh/a (73.24 %) for the **V2**, while the replacement of traditional lightbulbs with LEDs (**V3**) reduce the electricity consumption by 17 197.66 kWh/a (31.21 %).

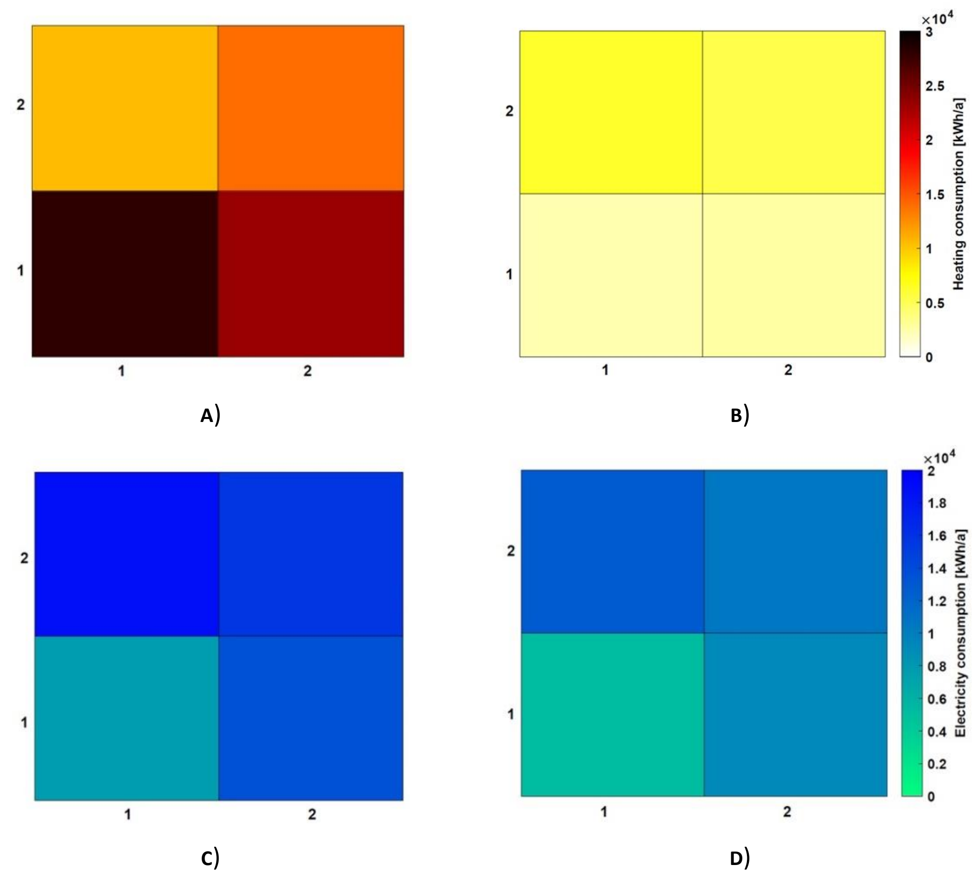


Figure 3.26. *The energy mapping for the analysed BC (example no. 1), accordingly:* ***A****) heating consumption –* ***V0*** *variant;* ***B****) heating consumption –* ***V2*** *modernization;* ***C****) electricity consumption –* ***V0*** *variant and* ***D****) electricity consumption with LEDs (****V3****)*

A)

B)

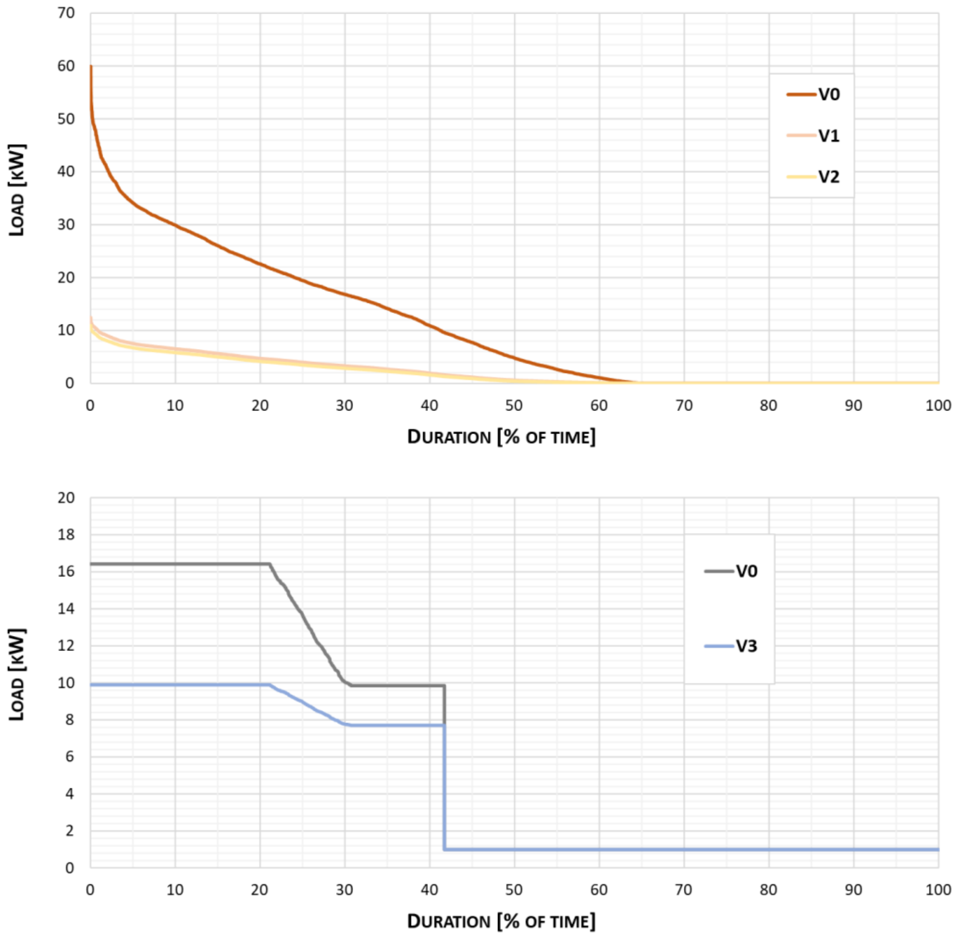


Figure 3.27. *LDCs of the analysed neighbourhood – A) heating and B) electricity demands for some of the examined scenarios*

For this BC, the application of solar energy is examined. In this scenario, the '*standard*' PVs (see more in subsection **3.7.4**) are applied to all the buildings within the analysed BC, considering '*on-grid*' technology. Whenever we considered the solar energy application, the proper definition of the input data is required.

In **Figure 3.28** we can see a comparison of electricity amounts, which are produced out of the applied PV systems, used instantly, sold to the grid as well as received back from the grid. Additionally, the solar energy application can be analysed using the time distributed electricity production; exemplary outputs are shown in **Figure 3.29**, for extreme summer and winter weeks. All the necessary calculations are performed for each building separately, thus the final outputs can be performed for a singular building as well for the whole area. The solar energy outputs are also included in a summary of the analysed BC (see **Table 3.19**).

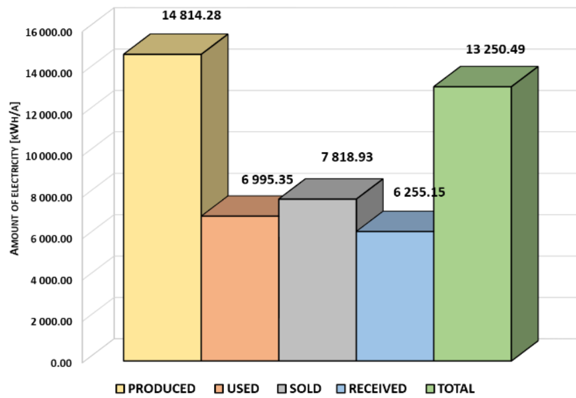


Figure 3.28. *Electricity shares related to the solar energy applications for the analysed zone*

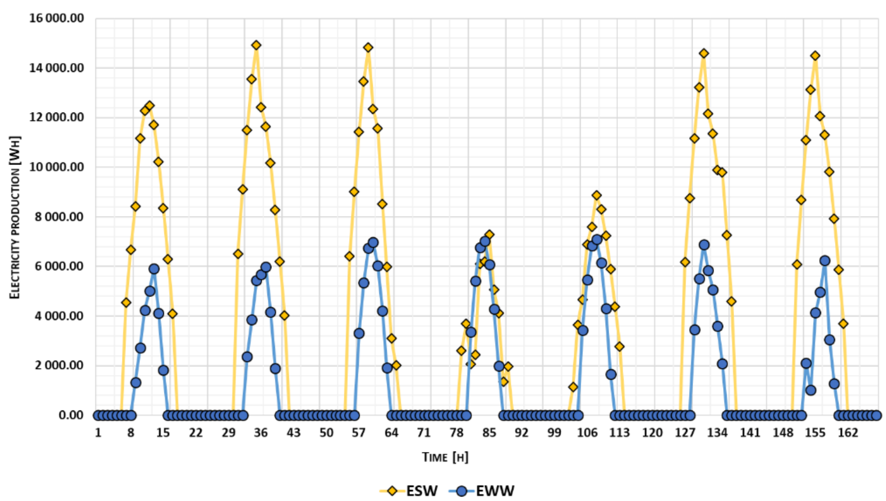


Figure 3.29. *A sum of electricity production (potential) out of the all applied PVs – extreme winter (EWW) and summer (ESW) periods for Lodz*

Table 3.16. *Summarized data for the RES applications in the analysed BC – example no. 1*

	PRODUCED	USED	SOLD	RECEIVED	TOTAL*
	[kWh/a]				[kWh/a]
SOLAR ENERGY	14 814.28	6 995.35	7 818.93	6 255.15	13 250.49

Where: * is a sum of the used and received electricity

The obtained results might be furtherly used*;* whenever any of the RES analysis is performed, those outputs might be included in the LDCs examination. In **Figure 3.30** the electricity LDCs of the analysed area are compared, for all the considered scenarios. Base variant (**V0**) and replacement of LEDs application (**V3**) are extended by the PVs usage (accordingly **V4** and **V5**).

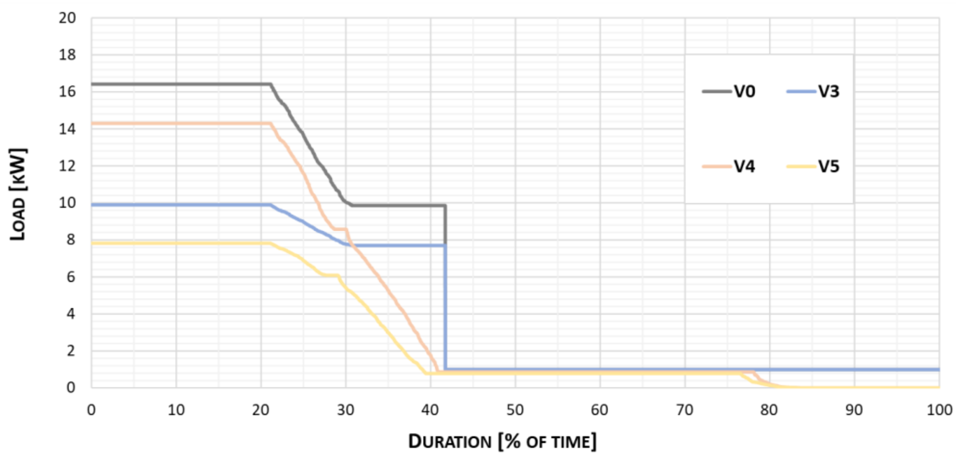
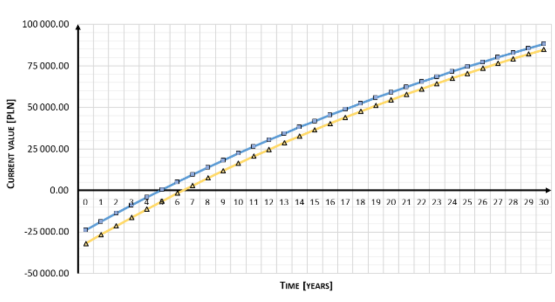
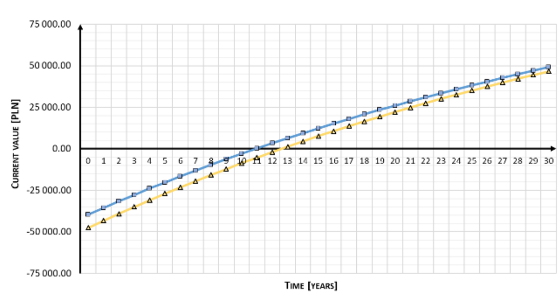


Figure 3.30. *Electricity LDCs of the analysed BC (example no. 1) – comparison of the all examined scenarios (RES included)*

The economic analyses can be performed using one of the three methods presented in subsection **3.7.6**. Using the *TEAC* software, it is possible to perform the economic analysis of the singular building, for all the buildings within the same type or the whole analysed area. In this example outputs from the economic examination are shown for each building because of the small size of the analysed area. The information when the proposed modernization payoffs are assembled in **Table 3.17** – the value in the table expresses a time (in years) after which the profit starts. Additionally, the LCC and NPV analyses are performed; in **Figure 3.31** and **Figure 3.32** we can see a comparison of the economic calculations for each building from the analysed BC. Moreover, it is possible to obtain economic outputs using maps – this approach is especially helpful for the larger areas studies, which high building congestion. It can be seen, that for RSFH_1 and RSFH_3 the proposed modernizations are profitable for both methods, while for RSFH_7 is not. For RSFH_5 the NPV method showed, that the proposed modernization is not profitable, while the LCC analysis reveals otherwise. The predicted payoff-times, as well as final profits, vary dependent on the used calculation method and building type (their energy-performance). The simplest method (the SPBT index) confirmed the above-mentioned conclusions.



A)



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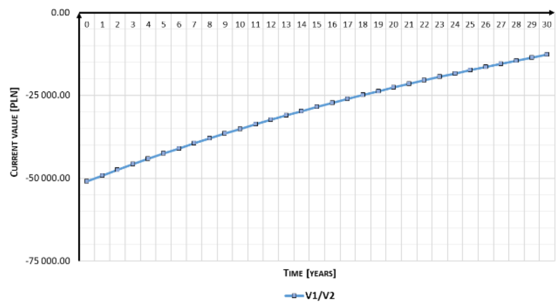

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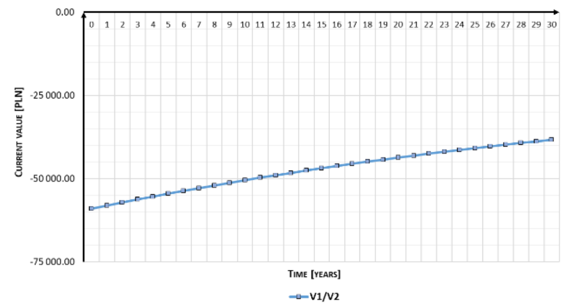
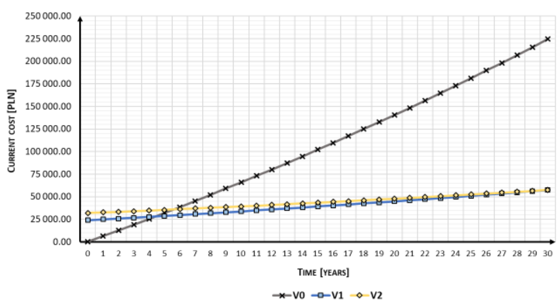
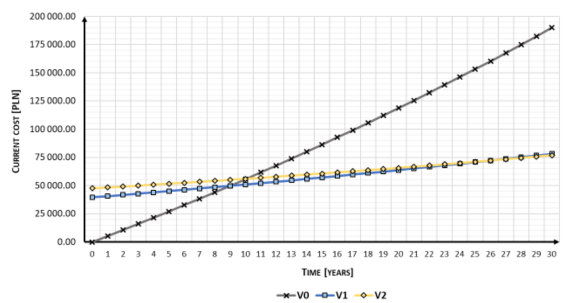


D)

Figure 3.31. *The NPV analysis for each building consisting the analysed BC – example no. 1, accordingly:* ***A****) RSFH_1;* ***B****) RSFH_3;(****C****) RSFH_5 and* ***D****) RSFH_7*



A)



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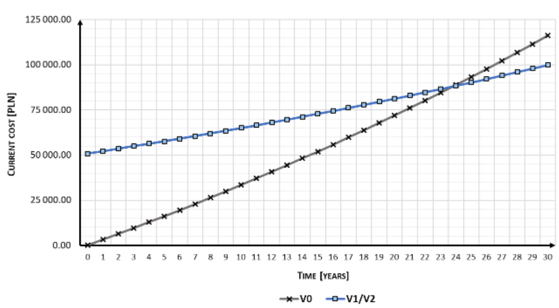

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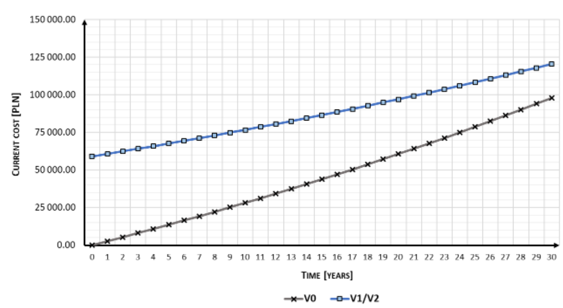


D)

Figure 3.32. *The LCC analysis for each building consisting the analysed BC – example no. 1, accordingly:* ***A****) RSFH_1;* ***B****) RSFH_3;* ***C****) RSFH_5 and* ***D****) RSFH_7*

Table 3.17. *Economic analysis outputs for example no. 1 – the payoff times summary for the* ***V2*** *scenario*

BUILDING ID	**BUILDING TYPE**	**SPBT**	**NPV_0** [YEARS]	**LCC_0**
1_1	RSFH_1	5.8	7	6
1_2	RSFH_3	10.8	13	11
2_1	RSFH_7	60.7	NP	44
2_2	RSFH_5	28.5	48	24

Where: **'NP'** means not profitable within the analysed period

Out of the emissions analyses, the amount of the produced GHG is estimated, for both scenarios (before and after proposed modernizations). In **Figure 3.33** we can see a comparison of maps with CO_2 emissions for the analysed neighbourhood. The '*after*' scenario (assigned as **V6**) is considered as a complex modernization, including buildings' thermal renovation (following the **V2** variant), the lighting systems upgrade, as well as the solar energy application (the **V5** scenario). Additionally, in **Table 3.18** a summary of GHG emissions is gathered.

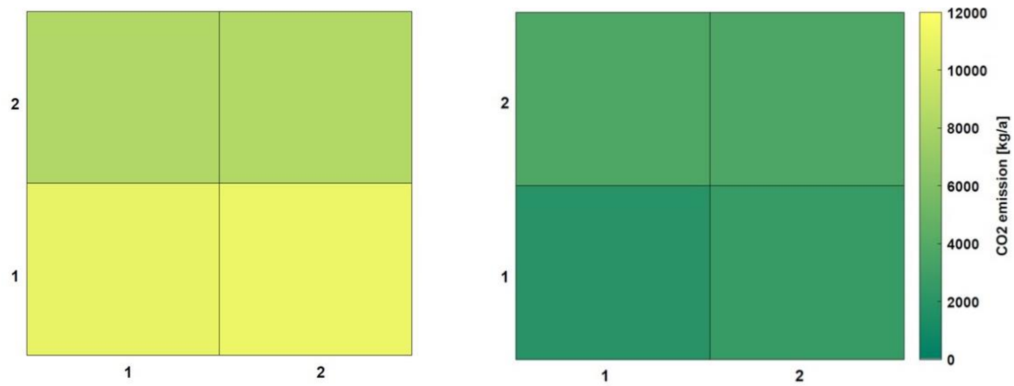


Figure 3.33. *The maps for the analysed BC – example no. 1: CO_2 emissions – **V0** variant (on left) and for complex modernization scenario – **V6** variant (on right)*

Table 3.18. *Summarized data for GHG emissions in the analysed BC – example no. 1*

EMISSIONS	BASE [kg/a]	V1[1] [kg/a]	V2[2]	LEDs[3] [kg/a]	RES[4]	COMPLEX[5] [kg/a]
CO_2	38 732.08	21 473.27	20 585.25	33 694.90	29 937.58	11 790.75
SO_2	519.26	323.86	290.77	427.22	358.57	130.08
NO_x	32.87	18.19	17.51	28.64	25.49	10.13
$PM_{2.5}$	90.01	36.97	28.35	81.30	74.80	13.14
PM_{10}	116.04	47.59	36.35	104.79	96.40	16.72

Where: [1] **V1** scenario; [2] **V2** scenario; [3] base variant with LEDs application (**V3**); [4] **V5** variant (application of solar energy and LEDs); [5] complex modernization (**V6**)

In the below table, the summarized data of the energy and environmental aspects are presented. In this collation, some scenarios are shown, based on a comparison of the following modernizations:

- **A** – the heating consumption before (**V0**) and after buildings refurbishments (**V2**),
- **B** – the electricity consumption with traditional (**V0**) and LEDs (**V3**) lightbulbs,
- **C** – base electricity consumption (**V0**) and with the solar energy application (**V4**),
- **D** – CO_2 emissions for the base variant (**V0**) and after all the considered modernizations (**V6**).

Table 3.19. *Summarized energy consumption data of the analysed BC – example no. 1*

SCENARIO	BEFORE	AFTER	REDUCTION
A [kWh/a]	76 004.42	16 644.75	59 359.67 (78.10%)
B [kWh/a]	55 820.46	38 146.77	17 673.69 (31.66%)
C [kWh/a]	55 820.46	42 569.97	13 250.49 (23.74%)
D* [kg/a]	38 732.08	11 790.75	26 941.33 (69.56%)

Where: * includes both heating and electricity consumptions

3.8.2. EXAMPLE NO. 2 – 6X5

The second simple example defined by means of the *TEAC* software is a rectangle-sized BC, 6x5 parcels. This area consists of 27 buildings, where three parcels remain empty (see **Figure 3.34**). This example is defined in the same way as the previous study, using the manual buildings selection (**DT1** method – see more in subsection **3.7.1**). The considered buildings distribution is summarized in **Table 3.20**. The procedure showing how to define the analysed area using the *TEAC* software is shown in section **A.7.2**. Other results are also shown in the above-mentioned section (**Appendix 7**); some heating and electricity LDCs are shown, but most importantly the comprehensive comparison of RES application, depending on the considered localization is performed.

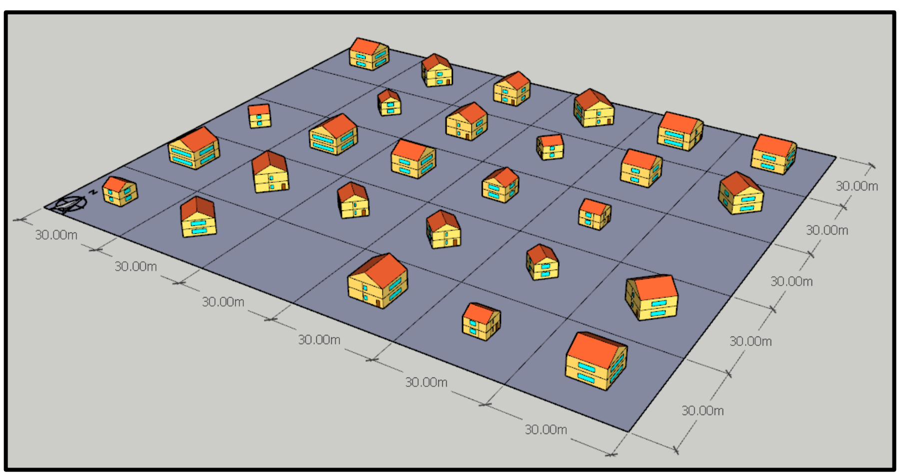


Figure 3.34. *Visualization of the analysed area consists of 27 buildings (BC 6x5; example no. 2)*

The main purpose of this example is to present the impact of different localizations (climate conditions) on the energy and environmental profiles of the analysed BC. Therefore, the performed analysis is made for all available localizations in the *TEAC* software. In this example, only two modernization variants resulting in lowering heating energy consumption were considered, accordingly, the base variant (assigned as **V0**) and **V1** scenario, assuming buildings enclose modernization (following the 2021 regulations) with the '*standard*' upgrade of the heating systems. Additionally, in order to decrease electricity consumption, some further scenarios are considered. The lighting systems modernization is considered (with LEDs), as well as solar and wind energy usage. The usage of wind energy is considered for the both onshore and offshore scenarios. From this point forward, the **V2** variant assumes simultaneously **V1** modernization and application of LEDs. The **V3** scenario assumes also the application of RES, accordingly solar and wind energy.

Solar energy is used the same way as it was introduced in example no. 1 (see subsection **3.8.1**), based on available and affordable roofs area in the analysed neighbourhood. Wind energy is analysed in three different scenarios, accordingly by application of the VAWT for all the buildings within the analysed area (**WE_A**), as well as the HAWT usage, for onshore (**WE_B**) and offshore (**WE_C**) cases. For the both scenarios of the HAWT applications, a single turbine is considered – produced electricity is therefore divided proportionally (based on buildings' occupied area) within all the buildings consisting the analysed BC. The instruction on how the above-introduced analysis is defined can be found in section **A.7.2**.

Table 3.20. *Buildings distribution summary – example no. 2*

BUILDING TYPE	NUMBER	$A_{o,tot}$ [m^2]	$A_{roof,total}$ [m^2]	$A_{roof,avail}$ [m^2]
RSFH_1	7	552.30	294.00	189.00
RSFH_2	3	297.60	172.50	86.25
RSFH_3	1	134.31	77.00	38.50
RSFH_4	4	559.68	320.00	200.00
RSFH_5	4	620.48	360.00	225.00
RSFH_6	4	688.16	406.00	355.25
RSFH_7	4	753.96	440.00	330.00
TOTAL	27	3 606.49	2 069.50	1 424.00

Where: $A_{o,tot}$ – total occupied area; $A_{roof,total}$ – total roof area; $A_{roof,avail}$ – available roof area (appropriate for the PVs)

The analysis of RES application can provide various results, which are always based on the hourly outputs of electricity productions for the considered source. As an example, the potential electricity production out of RES, for the examined neighbourhood located in Leba is shown in **Figure 3.35**, for a random one week period. The previously-mentioned figure shows a comparison, between application of both, onshore and offshore turbines, accordingly *HAWT_1S* and *HAWT_1O* models (see more in subsection **3.7.5**). In this case, also the usage of VAWT is examined, using *VAWT_1* model (one for each house). Also, an application of the '*standard*' PVs (see more in subsection **3.7.4**) are considered for this neighbourhood, considering '*on-grid*' technology. The performed analysis of RES application can be presented as a summarized data, as it is shown in **Table 3.21** – here the solar and wind energy potential is compared for the examined BC, located in Leba. The obtained outputs are furtherly used for additionally studies of the electricity consumption – in **Table 3.23** an application of both, PVs and VAWT is included. Additionally, a comprehensive comparison of RES potential for all examined localizations is discussed in **Appendix 7**.

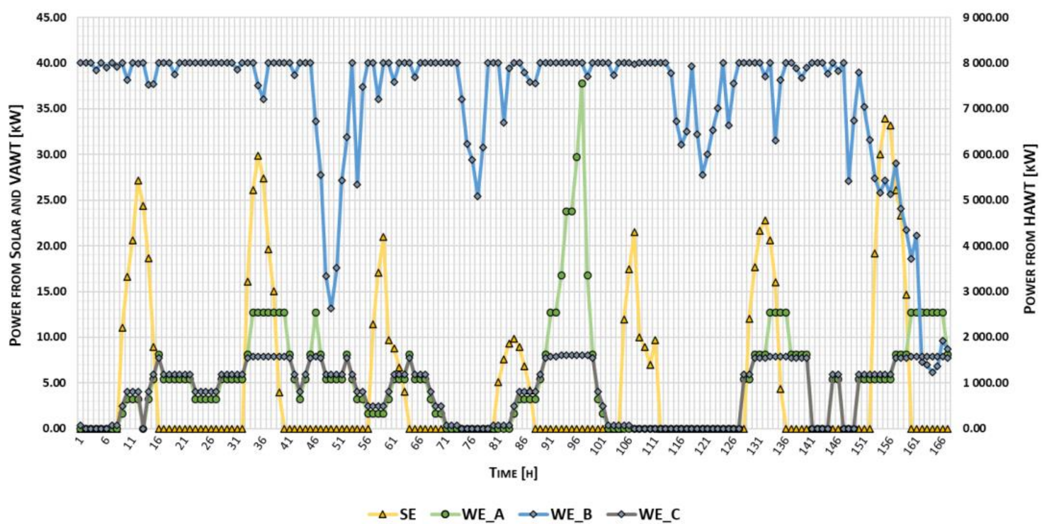


Figure 3.35. *An electricity production (potential) out of the applied RES – example no. 2 located in Leba*

Table 3.21. *Summarized data for RES applications in the analysed BC – example no. 2 located in Leba*

SCENARIO	PRODUCED	USED	SOLD	RECEIVED	FINAL*
	[kWh/a]				[kWh/a]
SE	86 498.80	35 051.63	51 447.17	41 157.74	76 209.37
WE_A	47 473.74	22 393.10	25 081.63	20 065.31	42 458.41
WE_B	4 665 784.00	78 352.09	N/A	N/A	N/A
WE_C	27 736 404.71	89 062.13	N/A	N/A	N/A

Where: * is a sum of the used and received electricity for **SE** and **WE_A** scenario or a used amount for **WE_B** and **WE_C** scenarios

The economic analysis is performed using the NPV method (see more in subsections **2.5.1** and **3.7.6**). This study is performed in order to check the profitability of the **V1** modernization variant, compering the Polish single-family houses sector for different localizations. The comparison is performed using the average NPV_0 values for each building type; they are presented in **Table 3.22**. Additionally, in **Figure 3.36** a collation of a NPV indexes distribution for all examined localizations is presented. The shown time-distributed values are expressing rates for all the buildings within the examined BC. It can be seen, that the proposed

BC modernization (**V1** scenario) has the fastest pay-back time for Bialystok (approx. 14 years) while the longest is observed for the Szczecin and Gdansk (approx. 19 years).

Table 3.22. *Economic analysis results presented with NPV_0 values – example no. 2*

	RSFH_1	RSFH_2	RSFH_3	RSFH_4	RSFH_5	RSFH_6	RSFH_7
GDANSK	8	8	16	13	NP	NP	NP
LEBA	7	7	14	11	NP	NP	NP
SZCZECIN	8	8	16	14	NP	NP	NP
PILA	8	8	15	12	NP	NP	NP
WROCLAW	8	8	15	13	NP	NP	NP
LODZ	7	8	15	12	NP	NP	NP
WARSAW	7	8	15	12	NP	NP	NP
BIALYSTOK	6	7	12	10	38	NP	NP
CRACOW	7	8	15	12	NP	NP	NP
RZESZOW	7	7	14	11	NP	NP	NP

Where: **NP** means '*non-profitable*' (pay-back time longer than 50 years)

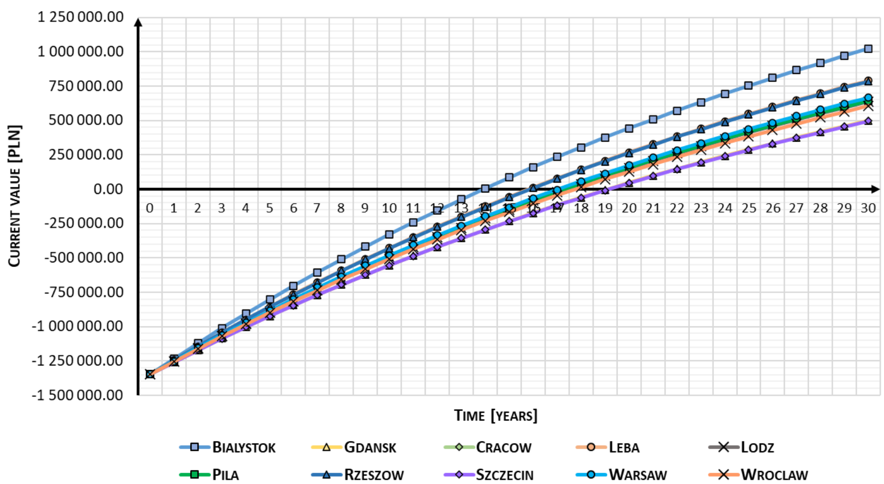


Figure 3.36. *Time-distributed NPV indexes for the examined BC in different localizations*

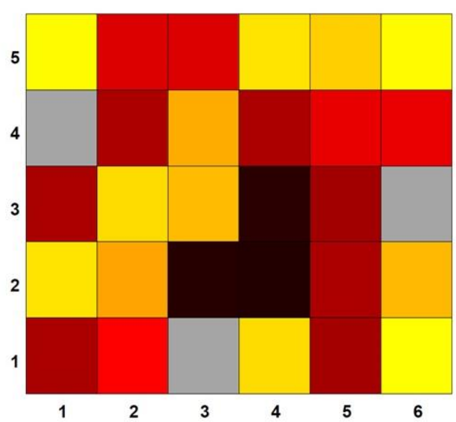
The main purpose of this example is to compare all the available localizations from the *TEAC* software database. The results of heating and electricity consumptions, as well as CO_2 emissions, for base (**V0**) and modernized scenario (**V3**), are shown in **Table 3.23**. Environmental examination (expressed with CO_2 emissions) includes both, heating and electricity consumptions; the base variants are assigned as '*before*' and modernized ones as '*after*'. Huge energy- and environmental-related potential is observed, while the economic profitability of the proposed modernization has been already proven.

Table 3.23. *Summarized energy-related data of the analysed BC – example no. 2*

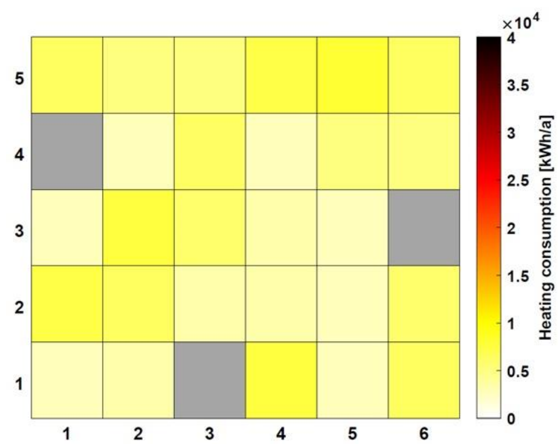
LOCALIZATION	H_c [MWh/a]		E_c [MWh/a]		E_{CO2} [t/a]	
	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER
GDANSK	519.28	99.58	272.55	90.98	233.23	63.52
LEBA	605.84	133.82	272.74	70.53	256.56	57.69
SZCZECIN	520.09	103.81	275.01	97.16	234.22	65.28
PILA	565.91	126.11	274.53	100.55	246.28	66.25
WROCLAW	552.89	116.00	277.51	93.31	243.88	64.19
LODZ	560.67	113.17	275.51	92.41	245.35	63.93
WARSAW	568.39	119.53	277.13	84.58	248.03	61.70
BIALYSTOK	678.15	169.07	271.99	105.10	275.60	67.55
CRACOW	566.46	125.52	277.97	90.19	247.63	63.30
RZESZOW	604.59	131.48	277.37	88.51	257.79	62.82

Where: **H_c** – heating demand; **E_c** – electricity demand; **E_{CO2}** – CO_2 emissions

Finally, some of the results are shown using maps. The default set of maps is shown in **Figure 3.37**, for Leba localization. The comparison of heating consumption is shown for the **V0** and **V1** scenarios, while for electricity consumption and CO_2 emissions for the **V0** and **V3** scenarios. Again, maps with emissions include the impact of both, heating and electricity consumptions.



A)



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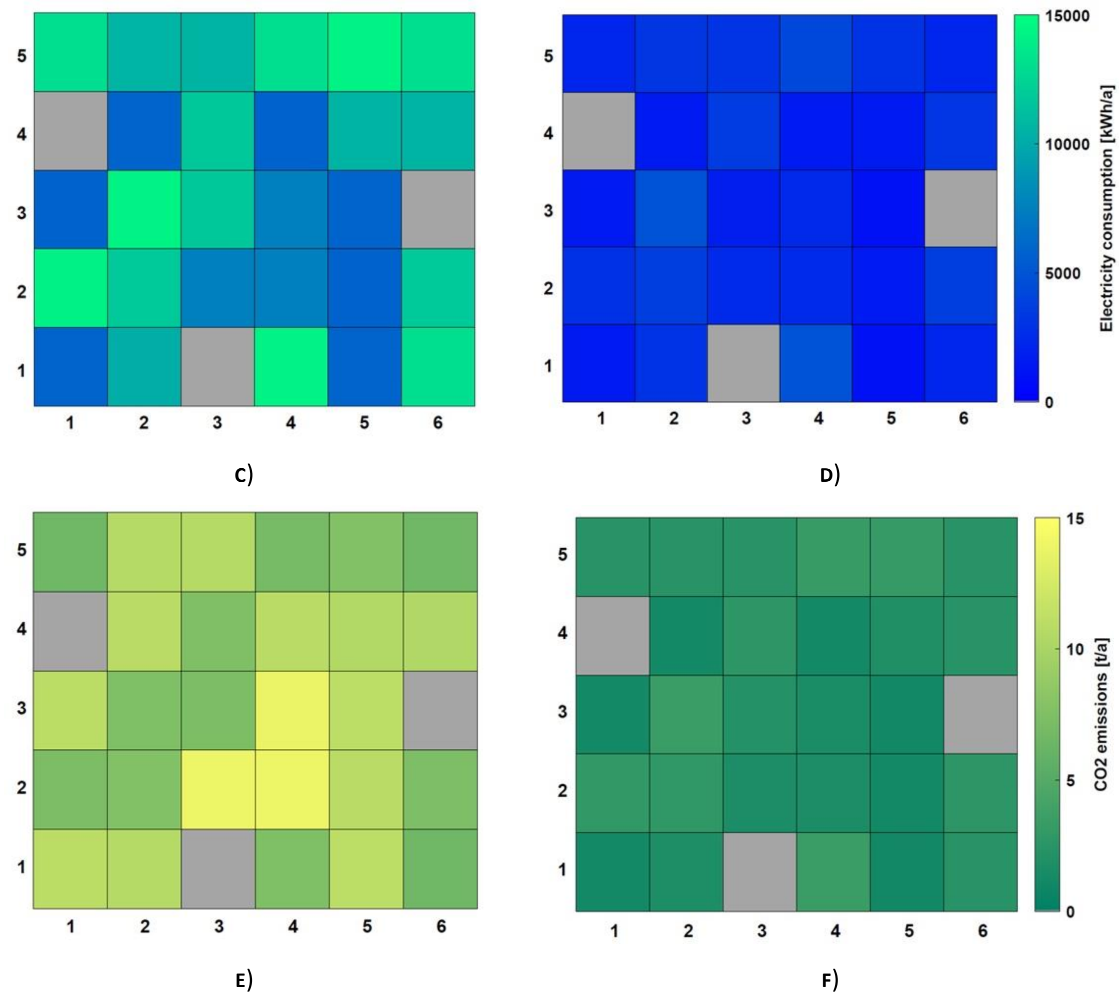


Figure 3.37. *The energy and environmental mapping of the analysed BC (example no. 2) located in Leba:* ***A)*** ***V0*** *heating consumption ;* ***B)*** ***V1*** *heating consumption;* ***C)*** ***V0*** *electricity consumption;* ***D)*** ***V3*** *electricity consumption;* ***E)*** ***V0*** *CO_2 emissions and* ***F)*** ***V3*** *CO_2 emissions*

4. BUILDING CLUSTERS ANALYSED BY MEANS OF THE *TEAC* SOFTWARE

In this chapter, the *TEAC* software application is presented using several examples of BECs. The performed analyses are chosen in order to fully present the potential of *TEAC* software and its' usability for those kinds of researches. Two very simple cases, concerning only 4 and 27 buildings, have been already shown in section **3.8**, while in this chapter, several hypothetical BECs, consisting of several hundred buildings are examined. The main purpose of those examples is to show some urban-scale analyses performed by means of the developed tool. The presentation of each example is focused on a different field; each case is summarized with a short conclusion.

4.1. BUILDING CLUSTER NO. 1 – 50X50 – RANDOM BUILDING PLACEMENT

In this example, a BC is established for an area consisting of 25 hundred single-family houses (see **Figure 4.1**), located in Lodz. Buildings' selection is performed automatically, using the **DT2** method (see subsection **3.7.1**). This example is focused on energy consumption analyses, based especially on LDCs. The buildings distribution of the analysed BC is summarized in **Table 4.1**. Some of the presented results have been already published in [281].

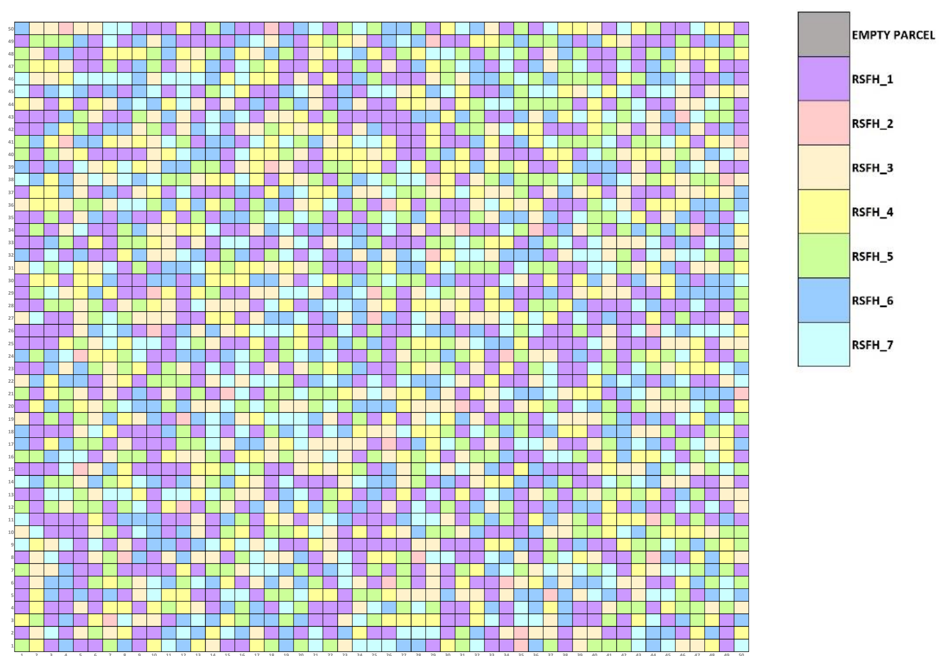


Figure 4.1. *Schema of the analysed area – BC no. 1*

In this study, several building modernizations are considered. Studying the heating energy consumption, six refurbishment variants are considered. The first three of them are related to building enclosure modernizations only, while the remaining ones also included heating systems upgrade (see more in section **3.5**). The examined scenarios are as follows:

- **V1** – buildings enclosure modernization following the BRV_1 scenario,
- **V2** – buildings enclosure modernization following the BRV_2 scenario,
- **V3** – buildings enclosure modernization following the BRV_3 scenario,
- **V4** – buildings enclosure modernization following the BRV_1 and HV_1 scenarios,
- **V5** – buildings enclosure modernization following the BRV_2 and HV_2 scenarios,
- **V6** – buildings enclosure modernization following the BRV_3 and HV_3 scenarios.

Table 4.1. *The summary of buildings distribution in the BC no. 1*

BUILDING TYPE	NUMBER	$A_{o,tot}$ [m²]	$A_{roof,total}$ [m²]	$A_{roof,avail}$ [m²]
RSFH_1	676	53 336.40	28 392.00	16 800.00
RSFH_2	38	3 769.60	2 185.00	2 185.00
RSFH_3	372	49 963.32	28 644.00	17 671.50
RSFH_4	333	46 593.36	26 640.00	17 400.00
RSFH_5	374	58 014.88	33 660.00	20 430.00
RSFH_6	369	63 482.76	37 453.50	23 903.25
RSFH_7	338	63 709.62	37 180.00	23 650.00
TOTAL	2 500	338 869.94	194 154.50	122 039.75

Where: $A_{o,tot}$ – total occupied area; $A_{roof,total}$ – total roof area; $A_{roof,avail}$ – available roof area (appropriate for PVs)

Studying the electricity consumption, a replacement of traditional lightbulbs with LEDs is considered (**V7** scenario). Additionally, an application of PV systems is proposed (see more in subsection **3.7.4**) – the **V8** scenario includes only instantly used outputs ('*off-grid*' system without batteries), while the **V9** involves also a recompensation received from the grid ('*on-grid*' system). In **Figure 4.2** the comparison of heating and electricity LDCs for the analysed area is presented; the base variant is assigned as **V0**.

It can be clearly seen, that variants **V1**, **V2** and **V3** resulted in a significant decrease in heating energy consumption. Additionally, those modernizations decrease the peak demands of the analysed area, simultaneously stabilizing the necessary heating load. The observed reduction in heating consumption is as high as 88 %. Heating system upgrades (variants **V4**, **V5**, **V6**) escalated the above-mentioned effects – the **V6** variant is the most profitable one in terms of heating consumption reduction. This variant decreased the annual heating consumption by approx. 96 % and lower the peak demand by 97 %. Moreover, the examined building modernizations reduced the duration of the heating season – the more comprehensive modernization, the shorter the heating period is. The presented outputs are obtained out of the heating demand predictions performed using the NN (see more in section **3.6**). Within the obtained predictions there are numerous values with a negligible heating demand, lower than 0.05 kW per building – it can be assumed, that those measures would not be applied in real life. Thus, it can be concluded, the proposed modernizations can reduce the duration of the heating season from approx. 5600 h to 3500 h only.

A)

B)

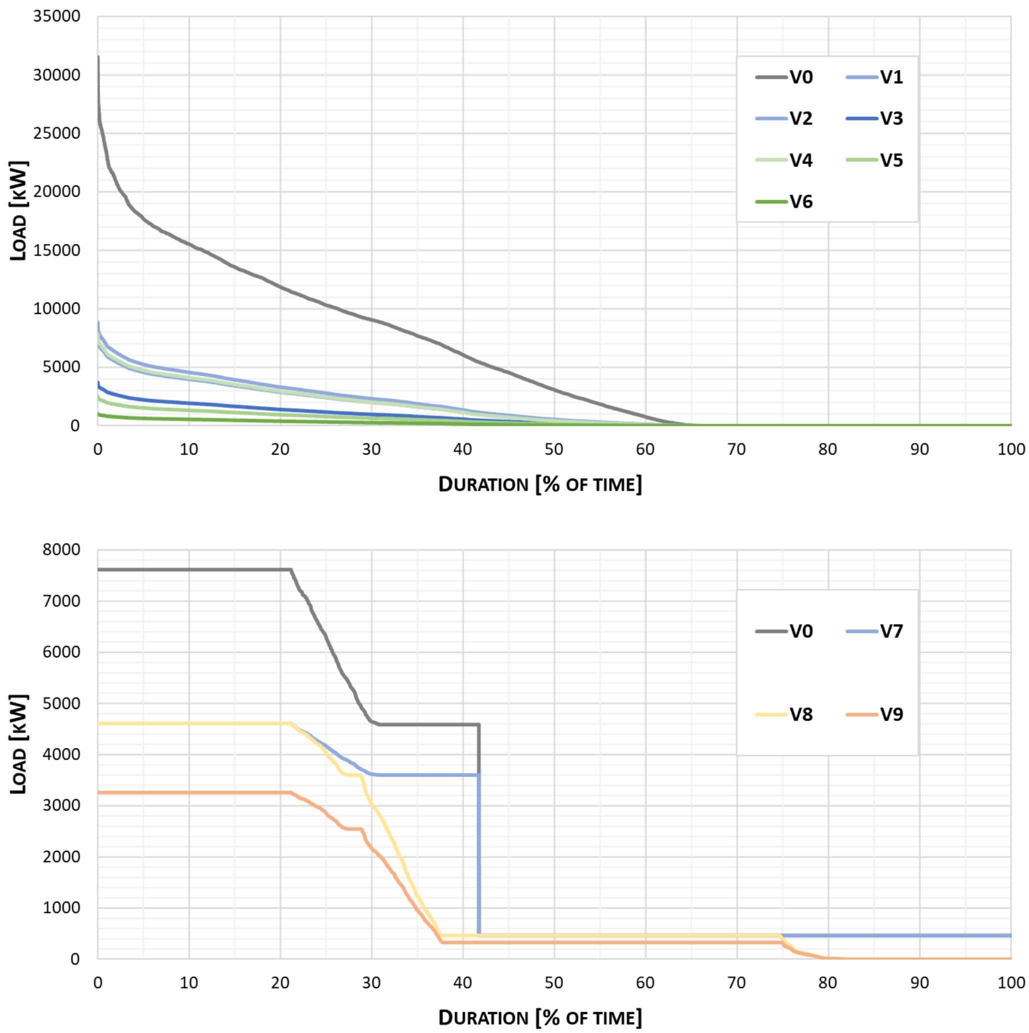


Figure 4.2. *LDCs for all the examined modernizations for the BC no. 1, accordingly:* A) *heating and* B) *electricity demands*

Having a look at the electricity LDCs it can be seen, that all of the proposed scenarios are lowering the electricity consumption, decreasing the peak demands, as well as stabilizing a load of a local grid. Thus, a significant improvement of the grid is obtained – the most beneficial one is the **V9** variant. The lighting system upgrade lowered the annual electricity consumption by about 31 %, while PVs application can furtherly decrease the consumption by up to 61 %. Moreover, thanks to the usage of solar energy the examined BC has zeroth electricity demand for approx. 1600 h.

A short energy-related summary of the performed analysis is presented in **Table 4.2**. It includes a comparison of the total electricity (**E_{TOTAL}**) and heating (**H_{TOTAL}**) energy consumptions as well as peak demands values (accordingly **E_{PEAK}** and **H_{PEAK}**) for all the examined variants. Additionally, more results of the analysed BC can be found in section **A.8.1**. The results presented using maps, as well as GHG emissions summary can be found in the above-mentioned section (**Appendix 8**).

Table 4.2. *An energy-related summary for the BC no. 1*

VARIANT	H_{TOTAL} [MWh/a]	H_{PEAK} [MW]	E_{TOTAL} [MWh/a]	E_{PEAK} [MW]
BASE	49 850.42	31.53	25 904.94	7.62
V1	13 457.56	8.81	N/A	N/A
V2	11 687.05	7.65	N/A	N/A
V3	5 651.97	3.69	N/A	N/A
V4	11 919.31	7.85	N/A	N/A
V5	3 806.11	2.51	N/A	N/A
V6	1 572.92	1.04	N/A	N/A
V7	N/A	N/A	17 784.66	4.61
V8	N/A	N/A	14 329.56	4.61
V9	N/A	N/A	10 181.67	3.26

Where: **H_{TOTAL}** – total heating demand; **H_{PEAK}** – peak heating demand; **E_{TOTAL}** – total electricity demand; **E_{PEAK}** – peak electricity demand

CONCLUDING REMARKS

The results presented in this example prove, that various building refurbishments can provide significant savings in terms of heating consumption. Application of PVs and lighting system upgrade can also considerably decrease the electricity consumption of the region. Those actions not only reduce the energy consumption but also reduce the duration of necessary demands. Additionally, LDCs are a very helpful approach in order to assess, how the proposed modernizations affect the energy-profile of the examined BC. This example shows, that it is possible to analyse the local grid load using the *TEAC* software.

4.2. BUILDING CLUSTER NO. 2 – 50X50 – CITY CENTRE PATTERN

This example is focused on the economic and environmental aspects obtained out of the *TEAC* software application. This study is performed for two localizations, accordingly Rzeszow and Szczecin. Rzeszow is selected due to its profitable solar conditions, while Szczecin is a seaside city (profitable wind conditions). **Figure 4.3** shows the defined buildings distribution following a city centre pattern – the **DT3** method (see more in subsection **3.7.1**); buildings distribution is presented in **Table 4.3**. The defined BC consists of 25 hundred buildings (50 by 50 parcels), each with a randomly selected orientation. For the purposes of this example, two modernizations are analysed (see more in section **3.5**), accordingly buildings' enclosures in accordance with BRV_2 scenario (assigned as **V1**) and with the addition of heating system upgrade, following HV_1 scenario (**V2**). Some additional results are presented in section **A.8.2**.

Table 4.3. *Buildings distribution summary for the BC no. 2*

BUILDING TYPE	NUMBER	$A_{o,tot}$ [m^2]	$A_{roof,total}$ [m^2]	$A_{roof,avail}$ [m^2]
RSFH_1	400	31 560.00	16 800.00	10 668.00
RSFH_2	600	59 520.00	21 591.25	21 591.25
RSFH_3	400	53 724.00	18 749.50	18 749.50
RSFH_4	400	55 968.00	20 160.00	20 160.00
RSFH_5	400	62 048.00	22 500.00	22 500.00
RSFH_6	200	34 408.00	12 789.00	12 789.00
RSFH_7	100	18 849.00	11 000.00	6 820.00
TOTAL	2 500	316 077.00	181 400.00	113 277.75

Where: $A_{o,tot}$ – total occupied area; $A_{roof,total}$ – total roof area; $A_{roof,avail}$ – available roof area (appropriate for PVs)

Firstly, the economic aspects related to the examined BC are discussed. Using NPV or LCC method it is possible to obtain time distributed economic indexes related to buildings operation costs and compare them with ones from the base scenario. Also, the values of NPV_0 and LCC_0 (see more in subsection **3.7.6**) are obtained out of the economic analyses; those values can be additionally compared with the traditional SPBT index. It is possible to generate a map with a distribution of some economic indicators, allowing to select zones (within the examined neighbourhood), which are characterized by high financial profitability of buildings' modernization.

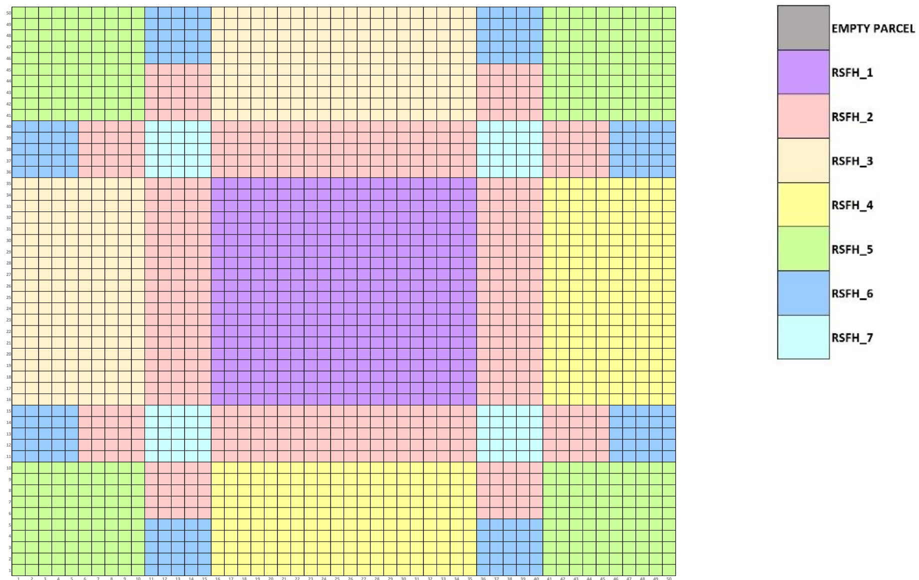


Figure 4.3. *Schema of the analysed area – BC no. 2*

In **Figure 4.4** the NPV analysis is presented, while results obtained out of the LCC method can be seen in **Figure 4.5** – both considered modernization variants are examined. As a reminder, whenever a variant line crosses the base-variant line, it means, that the proposed modernization starts to pay-off. For this example, all the presented results are sums for each building type, thus it is possible to easily notice when the proposed modernization is profitable for this particular house type. It is also possible to generate economic results for the whole buildings' combine – then the examined BC is considered as a unity. It can be clearly seen, that in general the older the building type (with poor thermal properties), the faster profits will be obtained. Additionally, despite the fact of different methods usage, a general trend remains the same – the both methods correctly estimate the potential profitability of buildings' modernization. Moreover, the economic analysis performed by means of the *TEAC* software allows distinguishing the most profitable building types or zones out of the analyzed BC. The modernization of the whole BC, in accordance with the **V1** scenario costs approx. 96.5 M PLN, while the **V2** variant about 122.3 M PLN. The annual savings varies from 10.2 M PLN/a, up to 11.9 M PLN/a, depending on the examined case. The pay-back time obtained out of the NPV analysis is between 10 and 14 years, while the LCC studies showed a range from 8 to 12 years. For the both analyses, the **V1** scenario is financially more beneficial. Additionally, in **Table 4.4** and **Table 4.5**, a comparison of economic results for each building type are summarized, for the all considered methods. It is possible, that for some RSFH the proposed modernisations are not profitable after a 50-years period. The obtained outputs are shown using the NPV_0 and LCC_0 indexes, which are explained in subsection **3.7.6**.

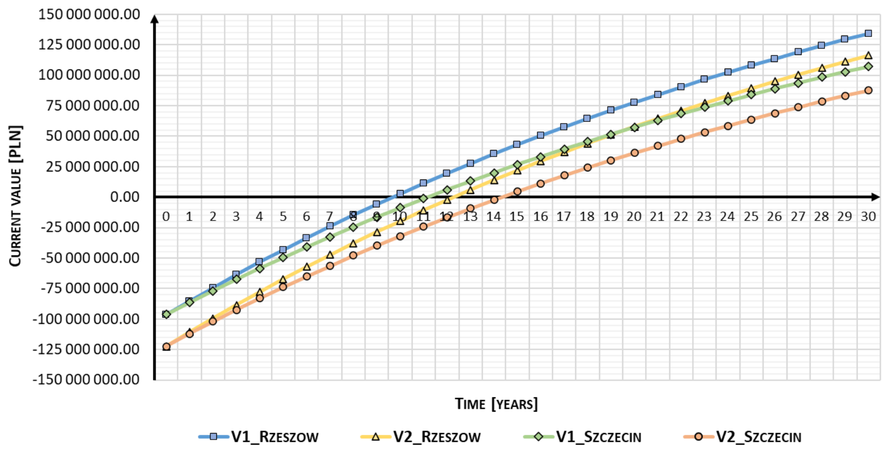


Figure 4.4. *NPV analyses of the proposed buildings modernizations for the analysed BC no. 2*

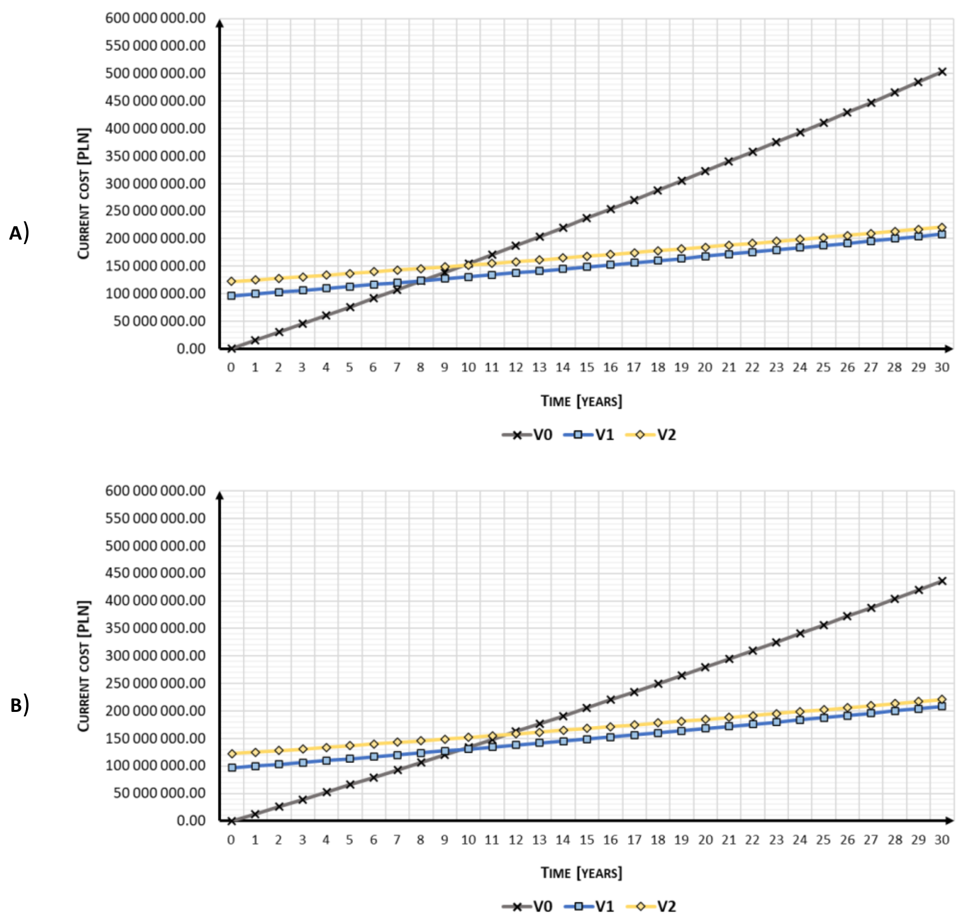


Figure 4.5. *LCC analyses of the proposed buildings modernizations for the analysed BC no. 2 located in:* **A**) *Rzeszow and* **B**) *Szczecin*

Table 4.4. *An economic summary of the performed analyses for the BC no. 2 located in Rzeszow*

BUILDING	SPBT [YEARS]		NPV_0 [YEARS]		LCC_0 [YEARS]	
TYPE	V1	V2	V1	V2	V1	V2
RSFH_1	4	6	5	7	5	6
RSFH_2	5	6	5	7	5	6
RSFH_3	8	11	10	13	9	11
RSFH_4	8	9	10	12	8	10
RSFH_5	24	28	41	NP	22	25
RSFH_6	53	63	NP	NP	44	50
RSFH_7	49	57	NP	NP	41	47

Where: **NP** means, that proposed modernization is not profitable after 50 years (valid for NPV and LCC analyses)

Table 4.5. *An economic summary of the performed analyses for the BC no. 2 located in Szczecin*

BUILDING	SPBT [YEARS]		NPV_0 [YEARS]		LCC_0 [YEARS]	
TYPE	V1	V2	V1	V2	V1	V2
RSFH_1	5	7	6	8	5	7
RSFH_2	5	7	6	8	6	7
RSFH_3	10	12	12	16	10	13
RSFH_4	9	11	12	13	10	11
RSFH_5	27	31	NP	NP	29	33
RSFH_6	61	72	NP	NP	NP	NP
RSFH_7	57	68	NP	NP	NP	NP

Where: **NP** means, that proposed modernization is not profitable after 50 years (valid for NPV and LCC analyses)

For the presented environmental analyses, RES (both solar and wind) usage is assumed. The analysed area is located in Szczecin, in order to compare the profitability of onshore and offshore wind energy applications. On the other hand, Rzeszow is selected because it has arguably one of the best solar conditions in Poland. The **V3** variant examines biomass usage instead of gas for heating purposes, after buildings refurbishment following the **V2** scenario. A comparison of GHG emissions for the both examined localizations and all modernizations (affecting the heating demand) is presented in **Table 4.6**. The overall GHG emissions decreased by up to 84.6 % for Rzeszow and 86.1 % for Szczecin cases. Some interesting results are obtained for the biomass usage (the **V3** scenario); CO_2, SO_2 and NO_x emissions are lower than for the previous variant (gas boilers in **V2** scenarios), while PM pollutions are notably higher. Despite the fact, that biomass combustion emits a noticeable amount of GHG, it is still the best solution out of the examined scenarios in terms of the overall environmental protection (see more about biomass in section **2.4**).

Table 4.6. *A comparison of GHG emissions out of the heating consumption for the BC no 2 in different localizations*

GAS TYPE	RZESZOW				SZCZECIN			
	V0	V1	V2	V3	V0	V1	V2	V3
CO_2 [t/a]	19 454.79	3 792.70	3 034.26	2 991.06	16 813.68	2 978.58	2 387.91	2 353.91
SO_2 [t/a]	198.63	28.31	0.05	0.32	172.65	22.05	0.04	0.26
NO_x [t/a]	16.62	3.28	2.70	2.38	14.36	2.57	2.13	1.87
$PM_{2.5}$ [t/a]	54.24	7.91	0.54	3.35	47.13	6.16	0.43	2.64
PM_{10} [t/a]	69.91	10.14	0.54	4.86	60.75	7.90	0.43	3.83

The remaining scenarios considered the application of solar and wind energy. The PV systems application are examined in the **V4** scenario, while the wind energy, produced out of the VAWT is applied to the **V5** variant. Moreover, the potential of a traditional HAWT is checked for onshore (both localizations) and offshore (for Szczecin) setups. The **V6** scenario assumes simultaneous usage of solar and wind energy – it is a mix of variants **V4** and **V5**. All the above-mentioned variants (from **V4** to **V6**) assumed biomass as a fuel used for heating purposes, as well as they included modernization of the lighting systems with LEDs.

The outputs, obtained out of the RES analyses are summarized in **Table 4.7** (for Rzeszow) and in **Table 4.8** (for Szczecin). Solar energy usage (assigned as **S**) is performed with the PVs, characterized with 21 % efficiency. The '*on-grid*' solar systems covering all the available roof-slopes within the examined BC – the total area of 58 885.20 m^2 PV panels are applied. It is possible to generate up to 8 948.32 MWh/a electricity in Rzeszow and 7 734.14 MWh/a in Szczecin out of the applied PVs. The system is capable to generate 10.41 MWp and 9.3 MWp, accordingly in Rzeszow and Szczecin. Wind energy is considered in three different scenarios. The **V5** scenario assumes the application of single VAWT for each building within the analysed BC; the *VAWT_1* from the *TEAC* software database is used (see more in subsection **3.7.5**). This case is assigned as **W1** and it is also considered as an '*on-grid*' system. In total, 2500 VAWT are applied to the examined BC. For the Rzeszow case, it is possible to generate 1 278.48 MWh/a electricity and 1 545.37 MWh/a in Szczecin. The **V6** scenario includes simultaneous application of both considered RES – it is assigned as a **SW**. The total electricity production (a sum of the electricity used and received from the grid) out of solar and wind combine is 8 992.83 MWh/a for Rzeszow and 8 233.15 MWh/a for Szczecin cases. The above-discussed scenarios might be considered as local actions – the systems are applied directly into buildings comprising the examined BC. The remaining two variants considered HAWT applications, accordingly for onshore (the both localizations) and offshore (only for Szczecin) scenarios. The number of the applied HAWT is assumed based on the peak electricity demand of the analysed area, as well as the technical parameters of applied turbines. Out of the available database of the *TEAC* software (see more in subsection **3.7.5**) the *HAWT_1S* is selected for onshore scenario (assigned as **W2**) while the *HAWT_1O* for offshore analysis (assigned as **W3**). The peak electricity demand for the analysed BC is approx. 4.3 MW; therefore 3 turbines were used for onshore and 1 for offshore study.

Table 4.7. *RES outputs for considered scenarios – BC no. 2 located in Rzeszow*

SCENARIO	PRODUCED	USED	SOLD	RECEIVED	TOTAL*
	[MWh/a]				[MWh/a]
S	8 948.32	3 383.44	5 564.87	4 451.90	7 835.34
W1	1 278.48	1 049.46	229.02	183.22	1 232.68
SW	10 226.80	4 056.96	6 169.83	4 935.87	8 992.83
W2	6 676.46	3 756.51	N/A	N/A	3 756.51

Where: ***** is a sum of the used and received electricity for the **S** and **W1** scenarios, and to used energy for the **W2** and **W3**

Table 4.8. *RES outputs for considered scenarios – BC no. 2 located in Szczecin*

SCENARIO	PRODUCED	USED	SOLD	RECEIVED	TOTAL*
	[MWh/a]				[MWh/a]
S	7 734.14	3 230.80	4 503.35	3 602.68	6 833.47
W1	1 545.37	1 218.75	326.62	261.30	1 480.05
SW	9 279.51	4 047.72	5 231.80	4 185.44	8 233.15
W2	7 735.13	4 115.82	N/A	N/A	4 115.82
W3	27 736.40	9 998.79	N/A	N/A	9 998.79

Where: ***** is a sum of the used and received electricity for the **S** and **W1** scenarios, and to used energy for the **W2** and **W3**

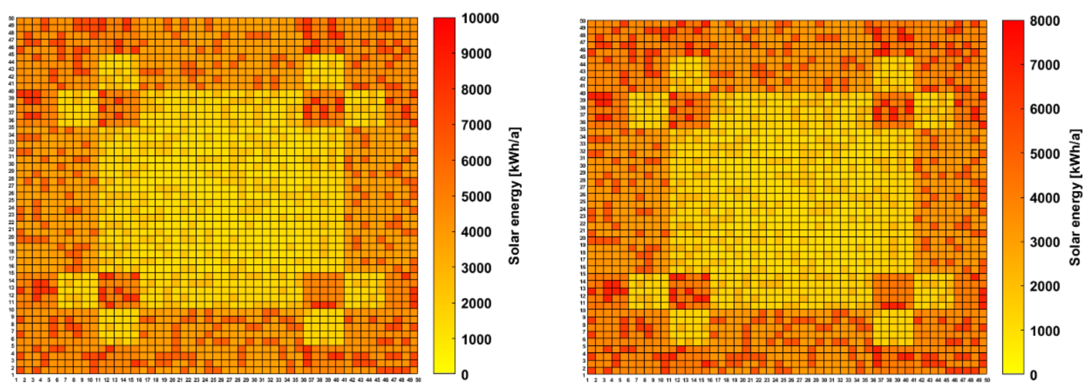


Figure 4.6. *Mapping of solar energy potential for the analysed area – BC no. 2, for Rzeszow (on left) and Szczecin (on right) localizations*

Additionally, it is possible to present some RES outputs by means of maps. As an example, the comparison of electricity generated by the PVs system for Rzeszow and Szczecin cases is presented in **Figure 4.6**.

A short energy-related summary of the performed analyses is presented in **Table 4.9** and **Table 4.10**. It can be seen, that all proposed modernizations improve the energy-efficiency of the examined BC. The heating energy consumption might be decreased by 83.3 % for Rzeszow and 84.8 % for Szczecin cases. The application of RES and lighting system upgrade provided a significant reduction in electricity demand: by approx. 68.5 % and 65.4 % for Rzeszow and Szczecin cases respectively. Moreover, a significant decrease in peak demands is obtained.

Table 4.9. *An energy-related summary for the BC no. 2 located in Rzeszow*

VARIANT	H_{TOTAL} [MWh/a]	H_{PEAK} [MW]	E_{TOTAL} [MWh/a]	E_{PEAK} [MW]
BASE	64 701.60	40.08	24 342.35	7.17
V1	12 852.53	8.23	N/A	N/A
V2	10 801.16	6.97	N/A	N/A
V4	N/A	N/A	8 818.78	2.85
V5	N/A	N/A	15 421.17	4.27
V6	N/A	N/A	7 661.16	2.68

Where: H_{TOTAL} – total heating demand; H_{PEAK} – peak heating demand; E_{TOTAL} – total electricity demand; E_{PEAK} – peak electricity demand

Table 4.10. *An energy-related summary for the BC no. 2 located in Szczecin*

VARIANT	H_{TOTAL} [MWh/a]	H_{PEAK} [MW]	E_{TOTAL} [MWh/a]	E_{PEAK} [MW]
BASE	55 895.25	34.59	24 135.60	7.09
V1	10 097.93	6.47	N/A	N/A
V2	8 500.33	5.49	N/A	N/A
V4	N/A	N/A	9 751.73	3.12
V5	N/A	N/A	15 104.73	4.22
V6	N/A	N/A	8 351.76	2.91

Where: H_{TOTAL} – total heating demand; H_{PEAK} – peak heating demand; E_{TOTAL} – total electricity demand; E_{PEAK} – peak electricity demand

Moreover, in section **A.8.2** some additional results are presented. The comparison of the heating and electricity LDCs, for Rzeszow and Wroclaw localizations, is shown. Additionally, some energy mapping of the analysed BC is presented. Finally, the NPV analysis, for the all building types is presented.

CONCLUDING REMARKS

This example is focused on economic and environmental analyses for large BC, considered in two localizations, accordingly Rzeszow and Szczecin. The above-mentioned localizations were selected in order to check the profitability of RES applications. Both solar and wind energy is highly profitable in terms of the obtained energy-related savings. The obtained results proved that Rzeszow has a profitable climate for solar systems usage, while Szczecin is suitable for wind turbines application. Traditional HAWT (especially offshore ones) has a huge potential in terms of supplying residential areas with electricity. All the proposed modernizations showed, that they are energy and environmentally profitable. Moreover, their short pay-back time proved economic profitability of the proposed scenarios. Also, the biomass application showed, that its' usage is a good solution towards environmental protection. The analyses performed for this example showed, that the *TEAC* software is an appropriate tool for energy, economic, and environmental-related analyses of residential BCs.

4.3. BUILDING CLUSTER NO. 3 – 50X50 – STREET-GRID PATTERN

This example focused on the results presented by means of area mapping. Some traditional heating and electricity consumption maps are shown, as well as emissions maps for all gasses considered in the environmental submodule of the *TEAC* software (see more in subsection **3.7.7**). The examined BC consists of 2189 single-family houses, in a square area, 50 by 50 parcels. A street-grid pattern (**DT4**) is used for buildings distribution within the analysed area (see more in subsection **3.7.1**). Some empty parcels are assumed. Additionally, buildings orientation is assumed based on the grid pattern – the front façade is always facing the street. This example is analysed for two different localizations, accordingly Wroclaw and Bialystok. Wroclaw is selected because it is considered as a warm region of Poland, while Bialystok has the coldest climate out of the *TEAC* software database. The assumed buildings distribution is visualized in **Figure 4.7** and their summary is presented in **Table 4.11**; the street scheme of the examined BC is shown in **Figure 4.8**. The following scenarios are considered (see more in section **3.5**):

- **V0**: base scenario,
- **V1**: building modernization following the BRV_1 scenario,
- **V2**: building modernization following the BRV_1 and HV_1 scenarios,
- **V3**: building modernization following the BRV_3 scenario,
- **V4**: building modernization following the BRV_3 scenario and HV_3 scenarios,
- **V5**: lighting system modernization with LEDs.

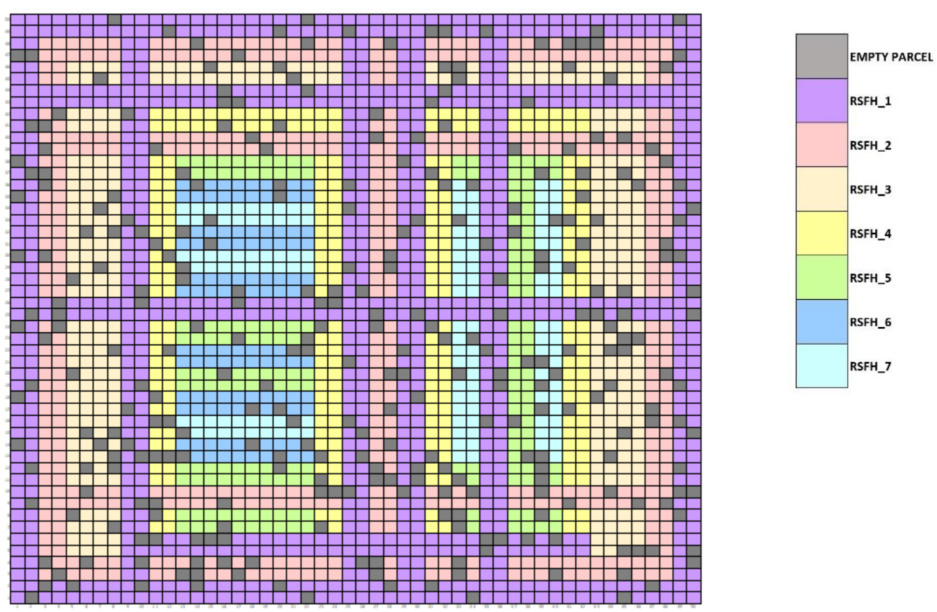


Figure 4.7. *Schema of the analysed area – BC no. 3*

Table 4.11. *Buildings distribution summary for the BC no. 3*

BUILDING TYPE	NUMBER	$A_{o,tot}$ [m^2]	$A_{roof,total}$ [m^2]	$A_{roof,avail}$ [m^2]
RSFH_1	839	66 197.10	35 238.00	24 276.00
RSFH_2	434	43 052.80	24 955.00	19 923.75
RSFH_3	279	37 472.49	21 483.00	21 483.00
RSFH_4	241	33 720.72	19 280.00	11 280.00
RSFH_5	160	24 819.20	14 400.00	12 645.00
RSFH_6	104	17 892.16	10 556.00	10 556.00
RSFH_7	132	24 880.68	14 520.00	10 340.00
TOTAL	2 189	248 035.15	140 432.00	110 503.75

Where: $A_{o,tot}$ – total occupied area; $A_{roof,total}$ – total roof area; $A_{roof,avail}$ – available roof area (appropriate for PVs)

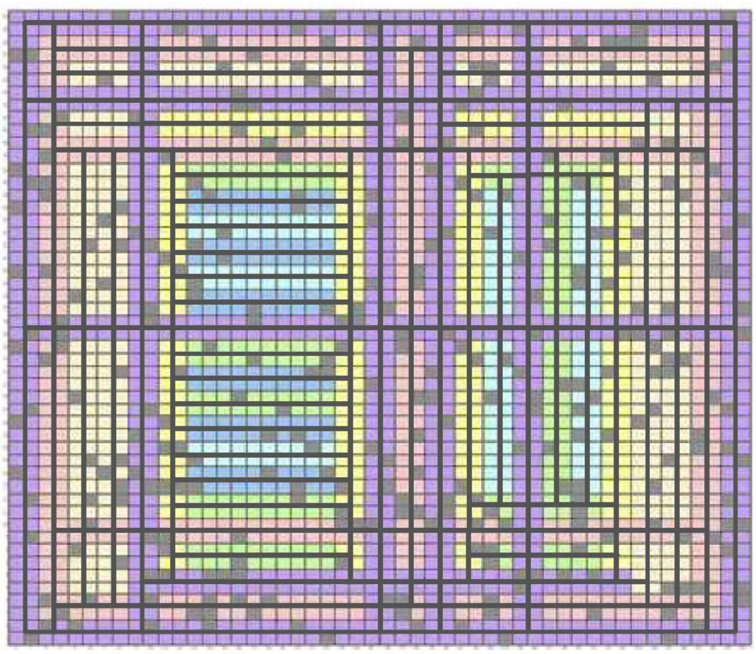


Figure 4.8. *The street scheme of the analysed area – BC no. 3*

In **Figure 4.9**, the comparison of heating and electricity consumption maps for the both considered localizations is presented. In the both cases, the base variant (**V0**) is compared with the **V4** scenario (for heating) and the **V5** scenario (for electricity). It can be clearly seen, that all the proposed modernizations improve the overall energy-efficiency of the analysed BC in the both localizations. Additionally, the Bialystok case is characterized by much higher heating demands (demonstrated with more intense colours) comparing with Wroclaw. There is no significant difference in the electricity demand distribution in the both localizations.

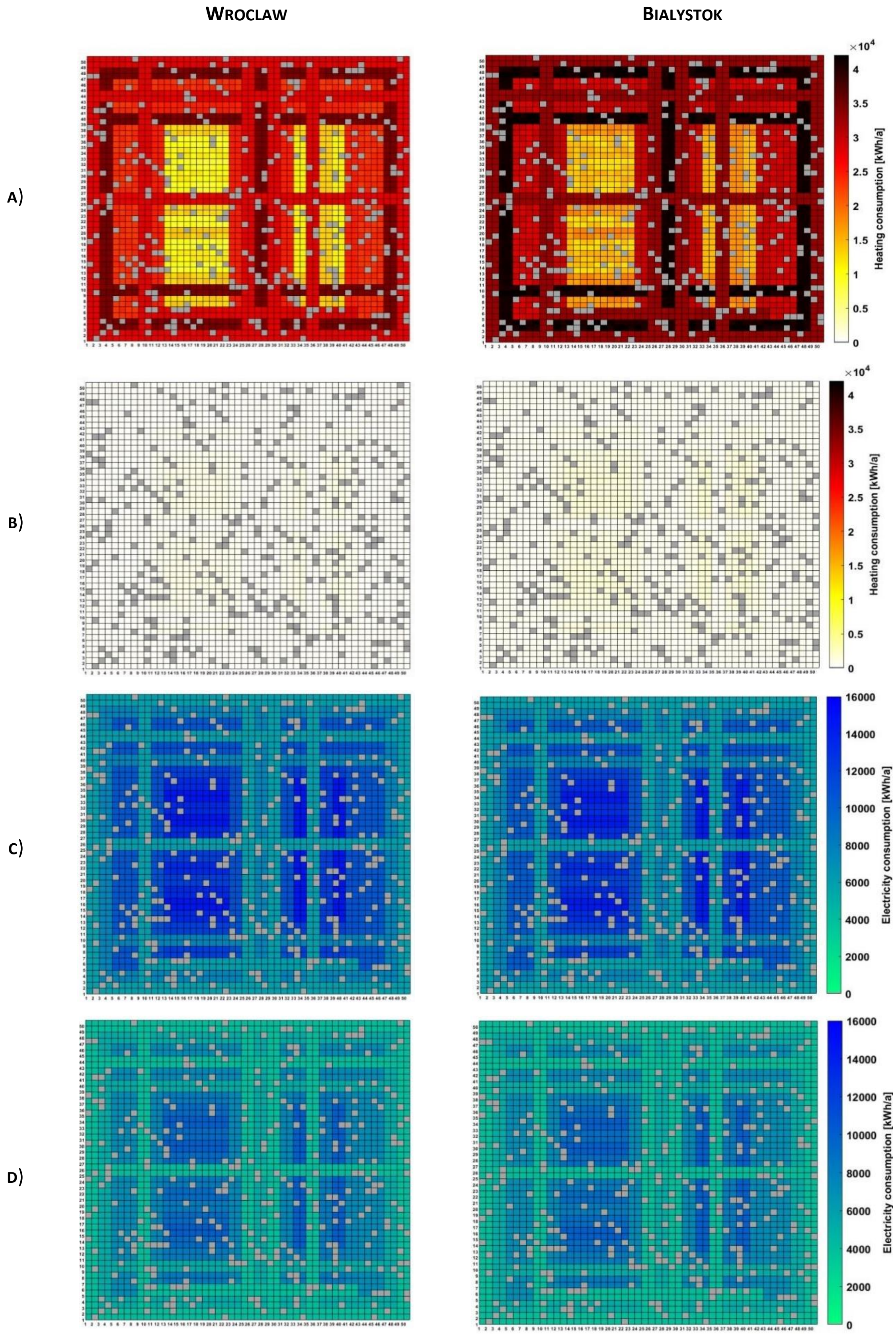


Figure 4.9. *Map outputs for the BC no. 3, for the different considered scenarios, accordingly:* **A)** ***V0*** *for heating;* **B)** ***V4*** *for heating;* **C)** ***V0*** *for electricity;* **D)** ***V5*** *for electricity*

Table 4.12. *Energy consumption summary for the BC no. 3 located in Wroclaw*

VARIANT	H_{TOTAL} [MWh/a]	H_{PEAK} [MW]	E_{TOTAL} [MWh/a]	E_{PEAK} [MW]
V0	55 213.90	33.89	19 035.31	5.62
V1	10 964.99	6.88	N/A	N/A
V2	4 626.07	2.90	N/A	N/A
V3	8 675.99	5.48	N/A	N/A
V4	1 148.03	0.72	N/A	N/A
V5	N/A	N/A	13 025.47	3.38

Where: $\mathbf{H_{TOTAL}}$ – total heating demand; $\mathbf{H_{PEAK}}$ – peak heating demand; $\mathbf{E_{TOTAL}}$ – total electricity demand; $\mathbf{E_{PEAK}}$ – peak electricity demand

Table 4.13. *Energy consumption summary for the BC no. 3 located in Bialystok*

VARIANT	H_{TOTAL} [MWh/a]	H_{PEAK} [MW]	E_{TOTAL} [MWh/a]	E_{PEAK} [MW]
V0	66 499.64	40.87	18 660.06	5.48
V1	15 807.45	9.92	N/A	N/A
V2	7 372.14	4.62	N/A	N/A
V3	12 512.51	7.91	N/A	N/A
V4	1 827.72	1.15	N/A	N/A
V5	N/A	N/A	12 900.39	3.34

Where: $\mathbf{H_{TOTAL}}$ – total heating demand; $\mathbf{H_{PEAK}}$ – peak heating demand; $\mathbf{E_{TOTAL}}$ – total electricity demand; $\mathbf{E_{PEAK}}$ – peak electricity demand

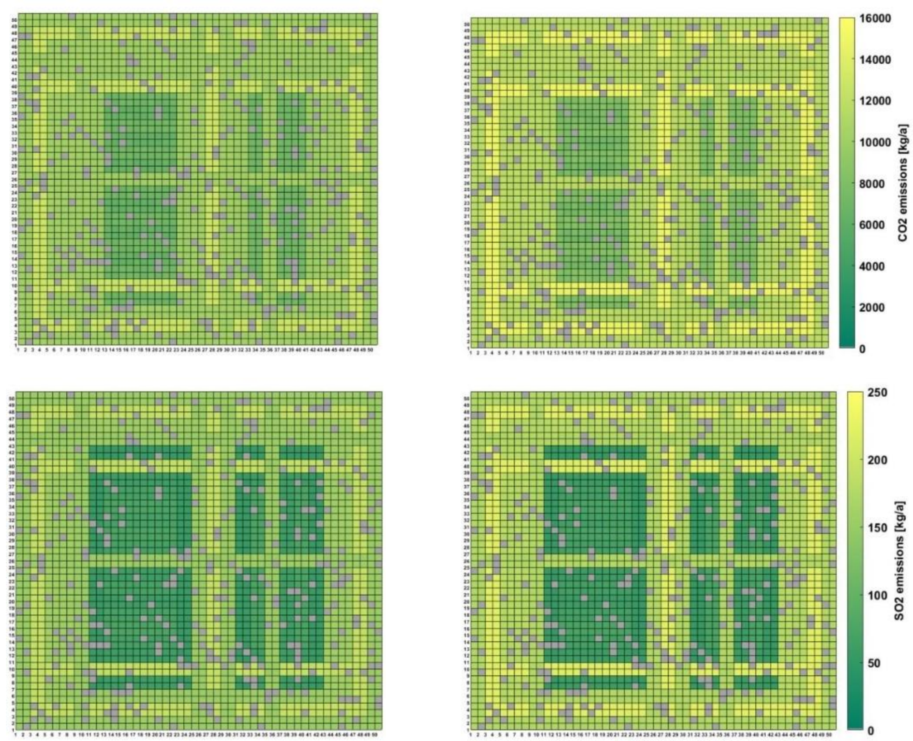
The energy consumption summary is presented in **Table 4.12** and **Table 4.13** – the heating and electricity consumptions are compared for the both considered localizations and all examined scenarios. It can be concluded, that outdoor climate conditions have a significant impact on the overall energy consumption (especially on the heating demand) within the examined area. For the base scenario (**V0**), the heating demand for BC located in Bialystok is higher by approx. 20 % comparing with the Wroclaw case. On the other hand, whatever the examined localization is, all the proposed modernizations provide similar effects in terms of energy-efficiency improvement. The more complex the modernization is, the higher reduction of peak demand, as well of annual consumption, is observed; for the Bialystok localization the above-mentioned reductions are lower than for Wroclaw. The **V4** modernization variant resulted in very high savings in heating consumption – approx. 98 and 97 % reductions are observed for Wroclaw and Bialystok respectively. It is worth underlining, that heating demand in Bialystok in the **V4** scenario is higher by 59 % compared with the Rzeszow case. The electricity consumption is quite similar for the both cities –the localization does not affect the electricity consumption by the house equipment. For the base scenario, the electricity demand is higher by approx. 2 % in Wroclaw, while after LEDs application is higher by approx. 1 %. The obtained reduction due to LEDs application is equal to 32 and 31 %, accordingly in Wroclaw and Bialystok. In the both cases, the electricity peak demand decreased significantly; it is lower by approx. 35 and 39 %.

Following the energy-efficiency improvement obtained thanks to the proposed modernizations, a reduction of GHG emissions is also achieved. The significantly higher heating demand for Bialystok localization resulted in higher GHG emissions comparing with the Wroclaw case. Different gasses emissions are presented as the comparison between the two examined localizations. The outputs incorporate emissions out of heating and electricity consumption combine. In **Figure 4.10** the base scenario (**V0**) is shown, while the results for the modernized area (**V4** and **V5** scenarios combined) are shown in **Figure 4.11**. The proposed modernizations significantly improved the environmental protection of the examined area – a major reduction in the all examined emissions is observed. Despite the localization, the obtained profits are unquestionable – the proposed modernizations are pro-ecological. In the comparisons presented in **Figures 4.10** and **Figures 4.11**, the data for Bialystok case are characterized by higher values of the examined emissions.

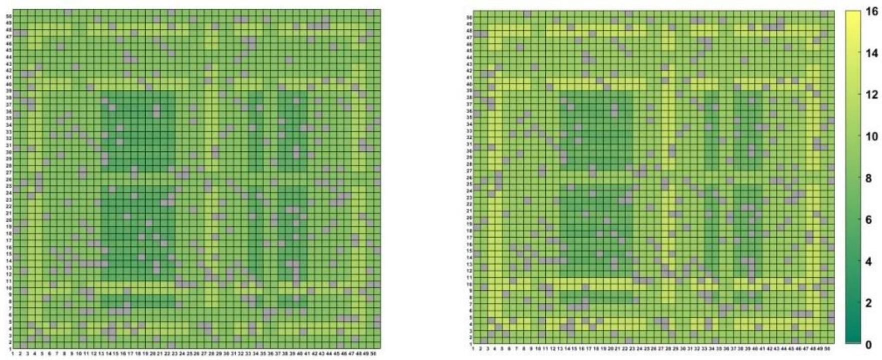
WROCLAW **BIALYSTOK**

A)

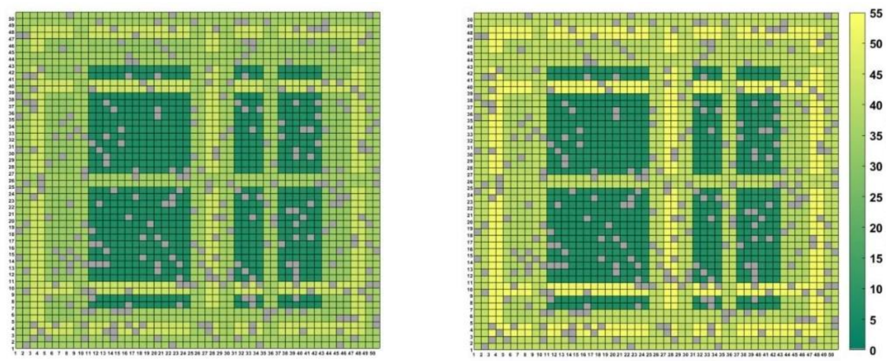
B)



C)



D)



E)

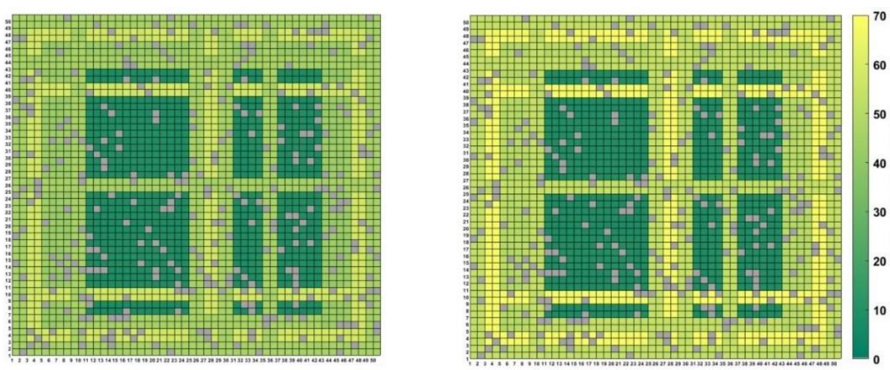
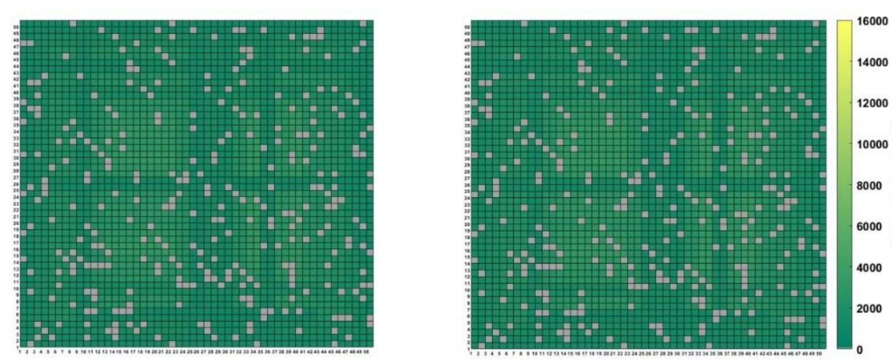


Figure 4.10. *Emissions maps for the BC no. 3, the base scenario (**V0**), accordingly for: **A**) CO_2; **B**) SO_2; **C**) NO_x; **D**) $PM_{2.5}$, **E**) PM_{10}*

WROCLAW **BIALYSTOK**

A)



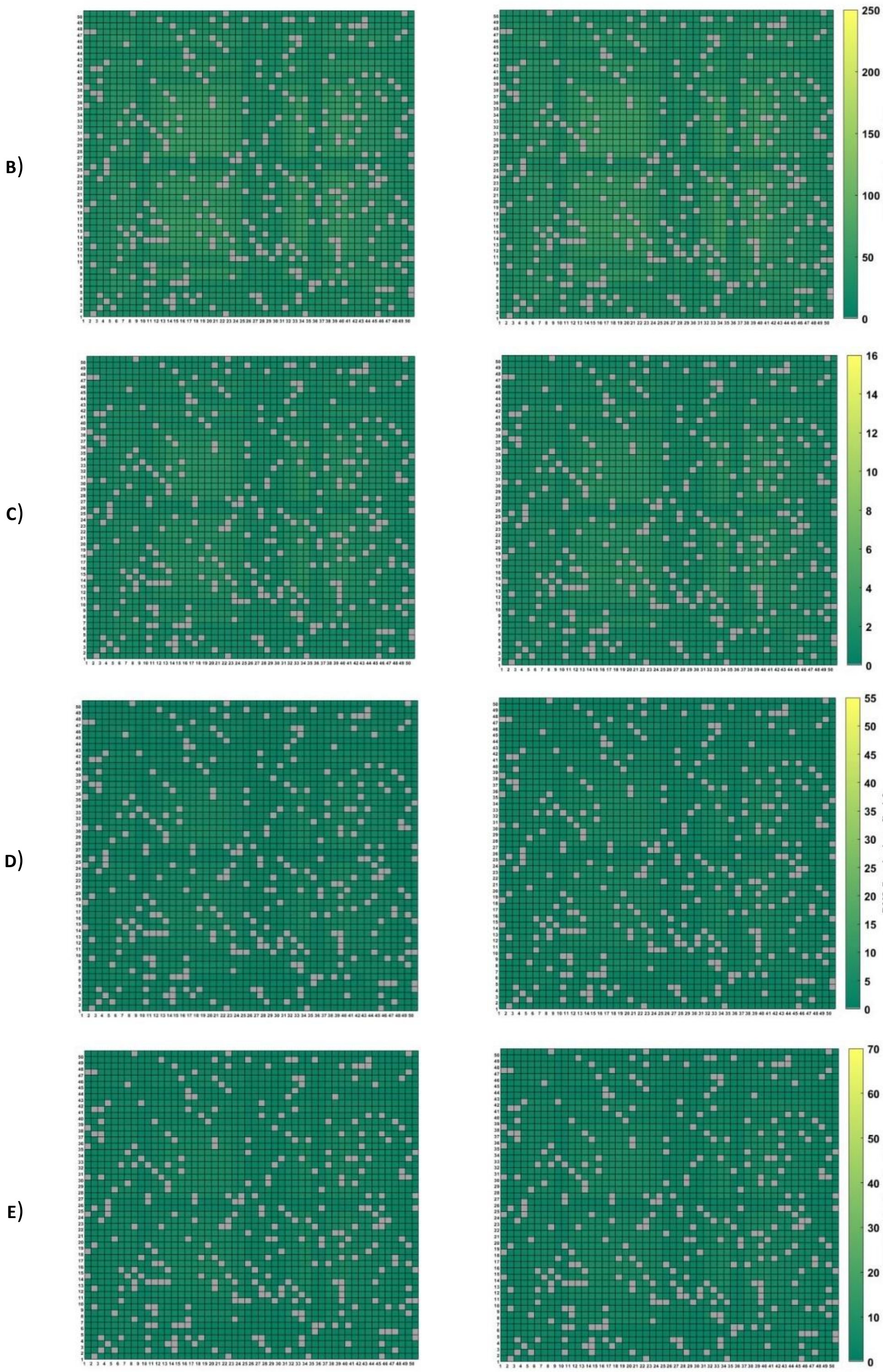


Figure 4.11. *Emissions maps for the modernized BC no. 3, accordingly for: A) CO_2; B) SO_2; C) NO_x; D) $PM_{2.5}$, E) PM_{10}*

The emission analyses are summarized in **Table 4.14**. The comparison confirmed outputs shown in the above maps – a significant reduction of GHG emissions is obtained for the both examined localizations. The overall emissions are higher for the Bialystok case, by approx. 14 % for the base scenario and by approx. 4 % after modernizations. The observed reduction in emissions after modernization stays within the range of 75 and 90 % (depending on the gas type and localization).

Table 4.14. *Emissions summary for the BC no. 3*

EMISSIONS	WROCLAW		BIALYSTOK	
	BEFORE [t/a]	AFTER [t/a]	BEFORE [t/a]	AFTER [t/a]
CO_2	22 213.15	4 039.59	25 521.38	4 197.66
SO_2	297.46	73.81	333.52	76.70
NO_X	18.80	3.39	21.62	3.52
$PM_{2.5}$	63.09	6.99	73.23	7.26
PM_{10}	81.46	9.02	94.55	9.37

Where: **BEFORE** – the base scenario; **AFTER** – the **V4** and **V5** scenarios considered simultaneous

CONCLUDING REMARKS

All the proposed modernizations are profitable in terms of energy and environmental aspects. Moreover, based on the presented results the impact of climate conditions on the overall energy consumption in the considered region is undeniable. Out of the localizations available in the *TEAC* software, the Bialystok has the harshest climate and it can be clearly observed by means of heating demand results. The difference in annual heating consumption between the examined BC located in Bialystok and Wroclaw is significant for the base scenario and it is even higher for the modernization scenarios. On the other hand, the electricity consumption is not meaningfully affected by the outdoor climate conditions for Polish localizations. The analysis of GHG emissions provided similar conclusions as the above-mentioned. This study shows, that it is possible to generate useful maps for residential regions by means of the *TEAC* software. Some additional results are shown and discussed in subsection **A.8.3**.

4.4. BUILDING CLUSTER NO. 4 – 50X80 – A NON-UNIFORM AREA

This example shows, that it is possible to define the neighbourhood based on the actual size and buildings distribution using the *TEAC* software. There are no limitations in terms of the analysed area size and shape – the area sizing and borders can be defined using empty parcels. Buildings distribution for the examined non-uniform BC, performed using the manual definition (**DT1**) is shown in **Figure 4.12**. The analysed area is a rectangle-based zone, 50 by 80 parcels, but it consists of only 1999 houses – buildings' type distribution is shown in **Table 4.15**, and their orientations are assumed randomly. For the purpose of this example, a comprehensive set of results is presented – that form of *TEAC* software outputs is recommended for BEC analyses.

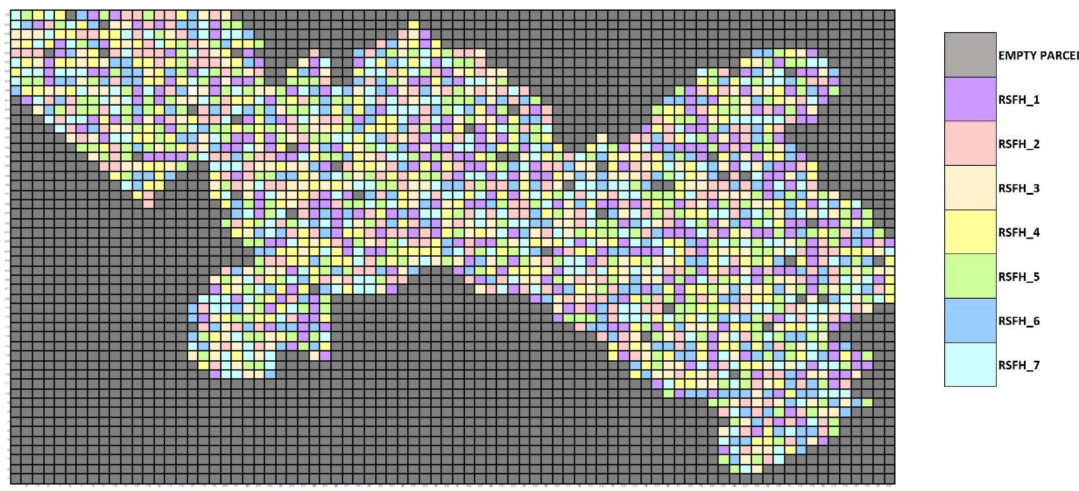


Figure 4.12. *Schema of the analysed area – BC no. 4*

Table 4.15. *Buildings distribution summary for the BC no. 4*

BUILDING TYPE	NUMBER	$A_{o,tot}$ [m^2]	$A_{roof,total}$ [m^2]	$A_{roof,avail}$ [m^2]
RSFH_1	299	23 591.10	12 558.00	7 812.00
RSFH_2	286	28 371.20	16 445.00	10 522.50
RSFH_3	285	38 278.35	21 945.00	13 937.00
RSFH_4	278	38 897.76	22 240.00	13 840.00
RSFH_5	302	46 846.24	27 180.00	17 280.00
RSFH_6	258	44 386.32	26 187.00	16 240.00
RSFH_7	291	54 850.59	32 010.00	19 910.00
TOTAL	1 999	275 221.56	158 565.00	99 541.50

Where: $A_{o,tot}$ – total occupied area; $A_{roof,total}$ – total roof area; $A_{roof,avail}$ – available roof area (appropriate for PVs)

The analysed BC is located in Warsaw. In this example following scenarios are considered:

- **V0** – the base scenario,
- **V1** – buildings' enclosures modernizations following BRV_2 scenario,
- **V2** – **V1** extended by heating systems modernizations, in accordance with HV_1 scenario,
- **V3** – **V1** extended by heating systems modernizations, in accordance with HV_2 scenario,
- **V4** – replacement of traditional lightbulbs with LEDs,
- **V5** – **V4** variant with solar energy usage (by means of PV systems applications),
- **V6** – **V4** variant with wind energy usage (by means of VAWT applications),
- **V7** – a combination of variants **V5** and **V6** (simultaneous usage of solar and wind energies),
- **V8** – a complex modernization (simultaneous consideration of **V3** and **V7** scenarios).

Firstly, the energy mapping outputs are shown. In **Figure 4.13** the comparison of heating demand maps is shown, while the electricity consumption maps are compared in **Figure 4.14**. Most of the examined scenarios (beside **V4** and **V8** variants) are presented. A significant improvement of the overall energy-efficiency for the examined BC is obtained. All the proposed modernizations improved the energy profile of the examined region by lowering energy consumption. The energy demand summary for each variant can be found in **Table 4.16**. The heating demand can be reduced by up to 92.3 %, while the electricity consumption, thanks to the RES application, can be lowered by 67.6 %.

Table 4.16. *Energy consumption summary for the BC no. 4*

VARIANT	H_{TOTAL} [MWh/a]	H_{PEAK} [MW]	E_{TOTAL} [MWh/a]	E_{PEAK} [MW]
V0	42 419.93	26.58	21 181.60	6.24
V1	10 025.51	6.51	N/A	N/A
V2	8 875.25	5.80	N/A	N/A
V3	3 249.77	2.13	N/A	N/A
V4	N/A	N/A	14 498.93	3.76
V5	N/A	N/A	8 385.83	2.68
V6	N/A	N/A	12 901.75	3.68
V7	N/A	N/A	6 872.68	2.46
V8*	N/A	N/A	9 991.28	4.17

Where: H_{TOTAL} – total heating demand; H_{PEAK} – peak heating demand; E_{TOTAL} – total electricity demand; E_{PEAK} – peak electricity demand; * – electricity data includes heating demand

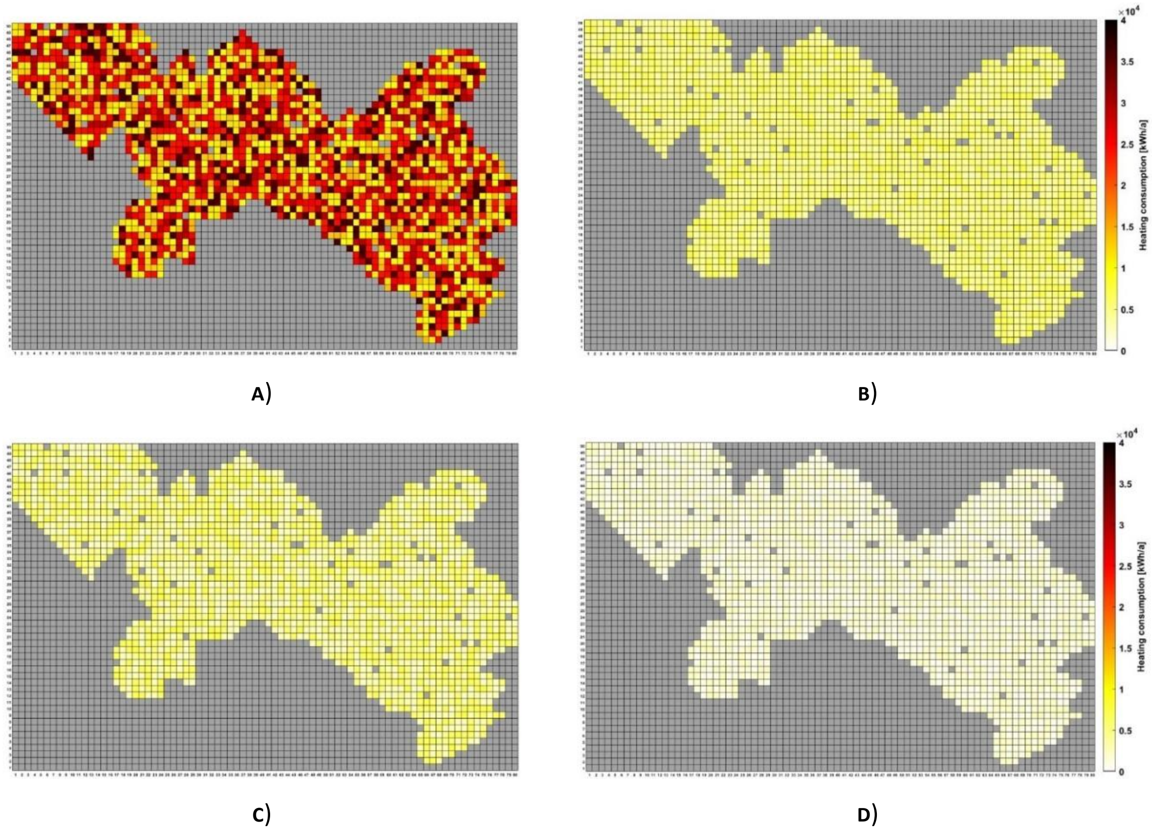


Figure 4.13. *Heating consumption maps for the BC no. 4 for the following scenarios:* ***A)*** ***V0****;* ***B)*** ***V1****;* ***C)*** ***V2****;* ***D)*** ***V3***

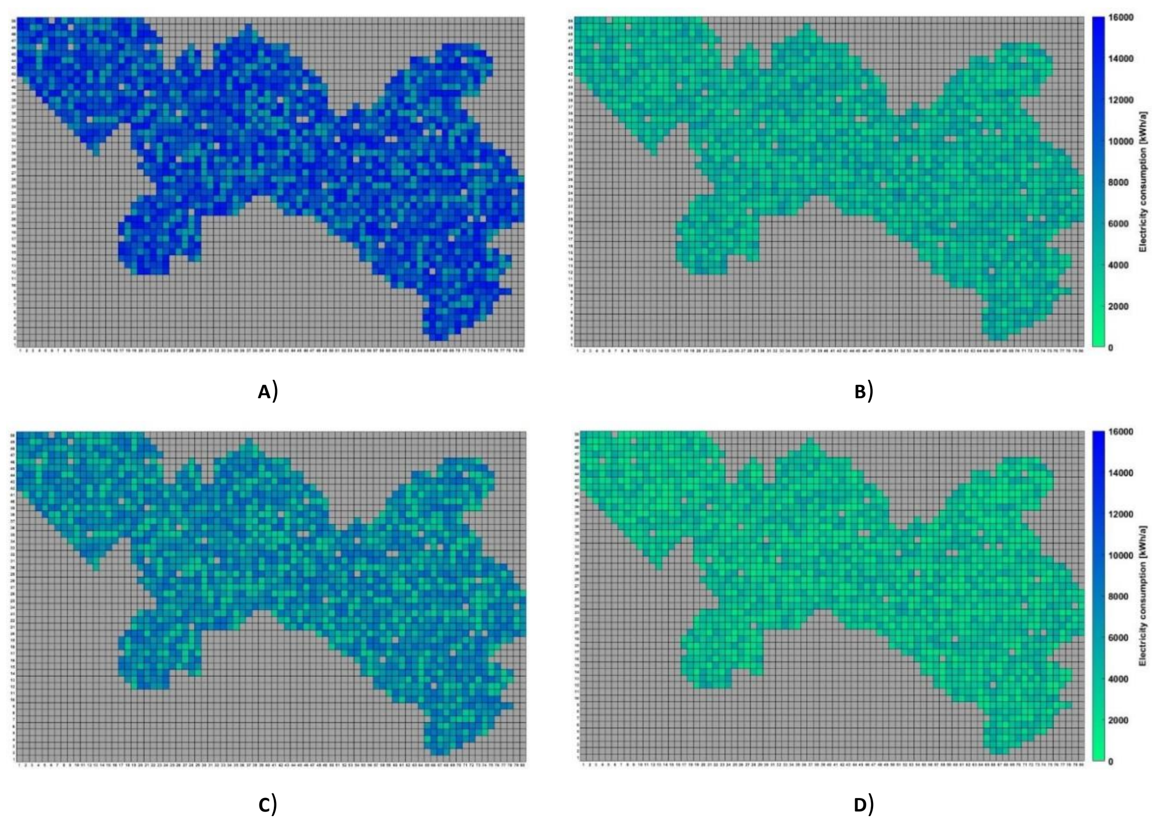


Figure 4.14. *Electricity consumption maps for the BC no. 4 for the following scenarios:* ***A)*** ***V0****;* ***B)*** ***V5****;* ***C)*** ***V6****;* ***D)*** ***V7***

The building's refurbishment is also analysed in terms of its financial profitability. The total cost of the **V3** modernization is approx. 198 M PLN; it will provide the annuals savings close to 7.8 M PLN/a. Based on the selected method, it will start to provide financial benefits after 23 years. The economic outputs of the LCC method are shown in **Figure 4.15** while for the NPV in **Figure 4.16**. In general, the proposed modernization variant (**V3**) is profitable for the whole examined BC. Additionally, it can be seen, that the proposed building's refurbishment method is not financially beneficial for some types of buildings comprising the examined region.

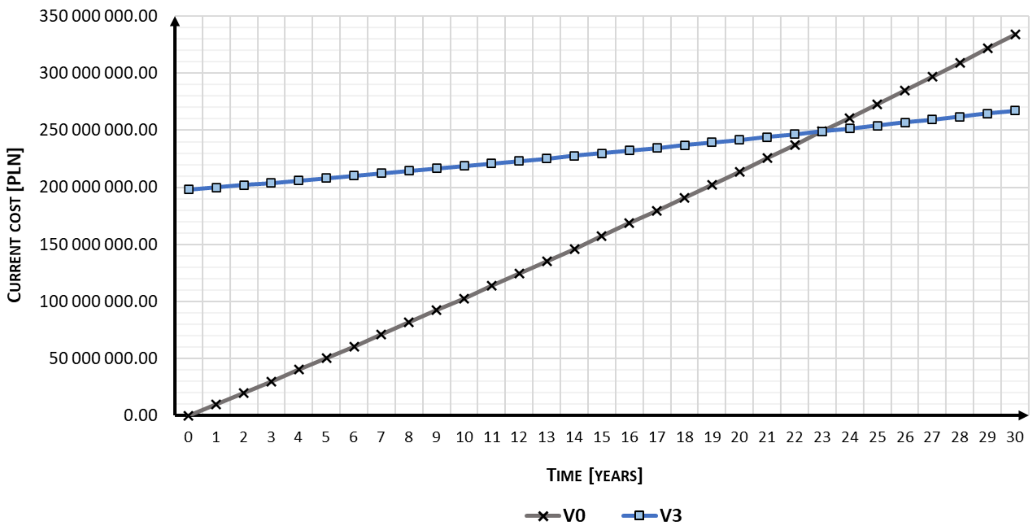


Figure 4.15. *LCC analysis for the BC no. 4 – comparison of the base (**V0**) and modernized (**V3**) scenarios*

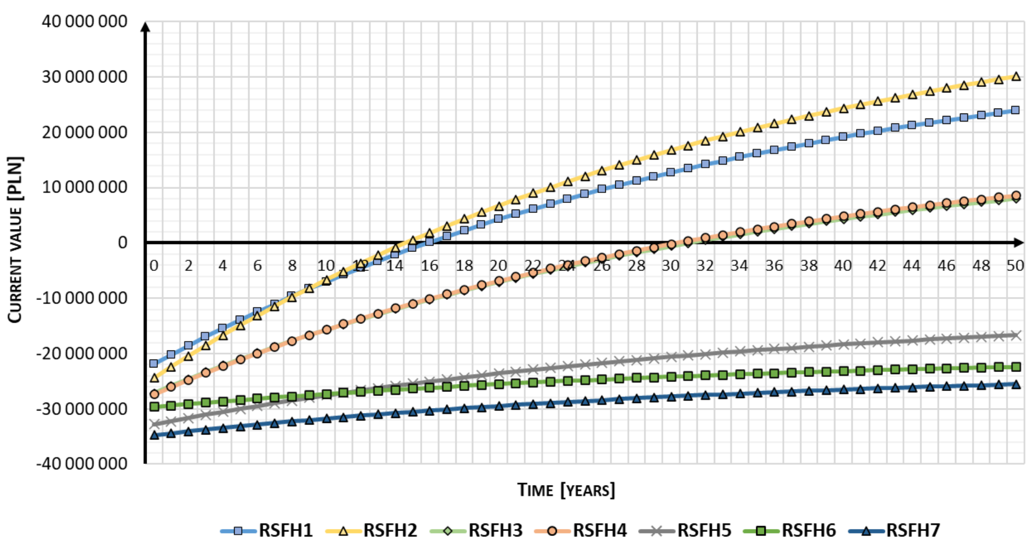


Figure 4.16. *NPV analysis for the proposed building modernization variant (**V3**) for BC no. 4*

Both, the solar and wind energy are considered in this example. A PV system is applied to each house on the available roof-slopes. Additionally, a single *VAWT_1* is applied for each building within the examined BC. The comparison of the potential electricity production from the applied RES is presented in **Table 4.17**. Additionally, the solar potential map of the analysed area is shown in **Figure 4.17**. Out of 53 440.20 m^2 of PVs, the total amount of 6 940 MWh/a electricity can be produced – it can cover 32.8 % of the local demand. Out of 1999 VAWTs the total amount of 1 670.3 MWh/a electricity is generated – it might cover up to 7.9 % of the total demand.

Table 4.17. *RES outputs for considered scenarios – BC no. 4*

SCENARIO*	PRODUCED [MWh/a]	USED [MWh/a]	SOLD [MWh/a]	RECEIVED [MWh/a]	TOTAL** [MWh/a]
V5	6 940.00	2 805.49	4 134.51	3 307.60	6 113.10
V6	1 670.30	1 302.88	367.43	293.94	1 596.82
V7	8 610.30	3 688.84	4 921.46	3 937.17	7 626.01
V8	8 610.30	4 336.44	4 273.86	3 419.09	7 755.53

Where: * scenarios show only electricity produced out of renewable energy systems (LEDs are not considered); ** is a sum of the used and received electricity

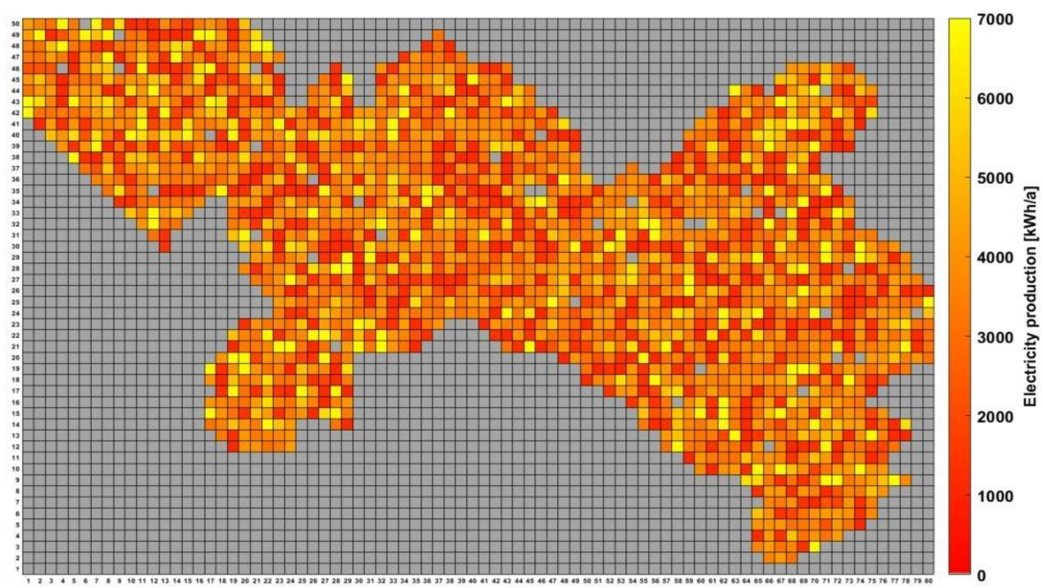


Figure 4.17. *Solar energy map for the BC no. 4*

Moreover, the examined BC is analysed by means of LDCs. In **Figure 4.18** the collation of heating and electricity demands is presented, for all the examined scenarios. The heating demand can be reduced by up to 92 %, while the peak electricity demand can be lowered up to 3 781.33 kW (60.6 %).

A)

B)

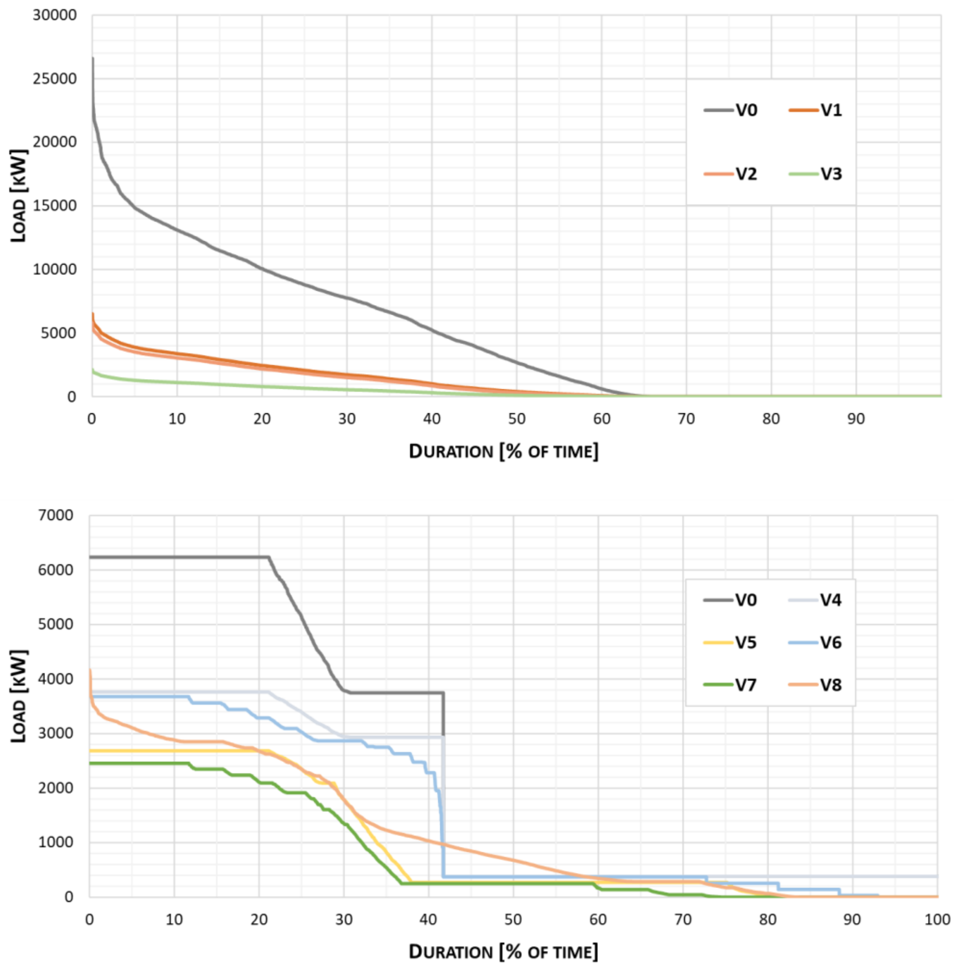
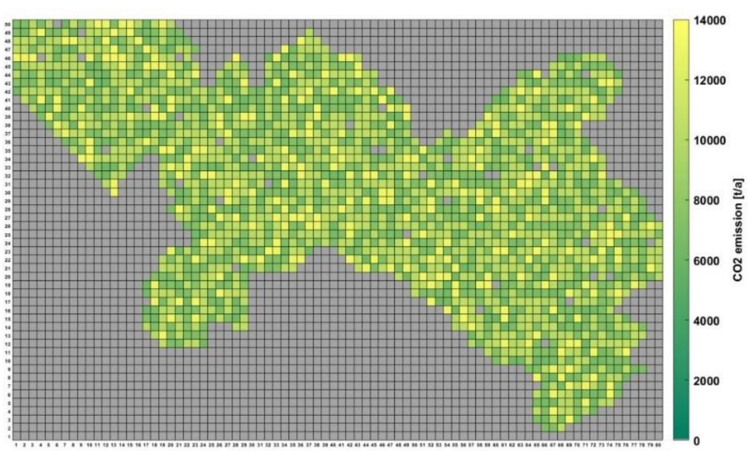


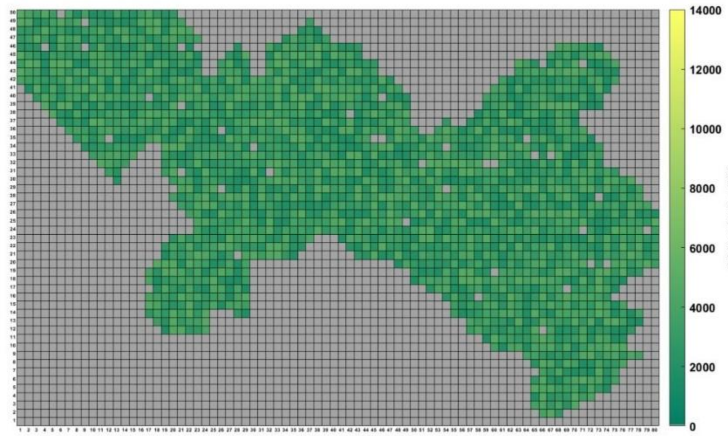
Figure 4.18. *LDCs comparison for proposed modernizations in the BC no. 4: A) heating and B) electricity*

The environmental analysis is performed by means of GHG emissions. The obtained outputs are presented using the CO_2 and PM_{10} emissions maps; the base variant (**V0**) is compared with the **V2** and **V8** scenarios (see **Figure 4.19** and **Figure 4.20**). The obtained CO_2 emission is lower by accordingly 64.5 % and 84.8 %, while PM_{10} emissions are decreased by 82.5 % and 88.2 %.

A)



B)



C)

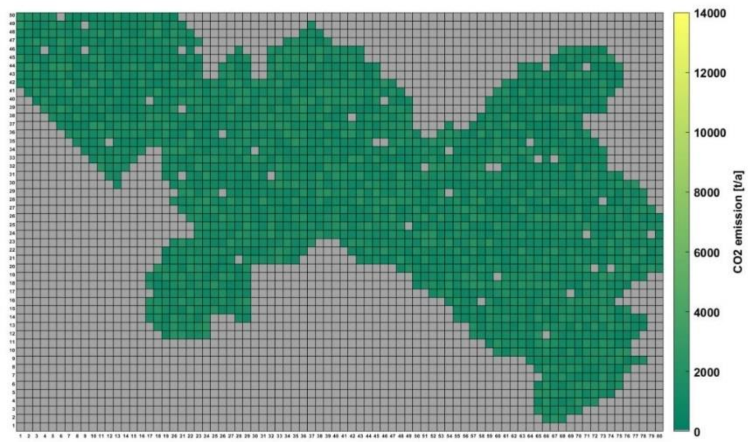
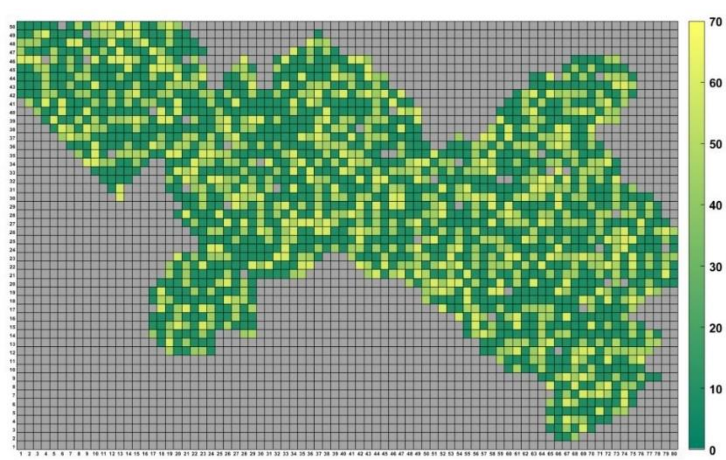
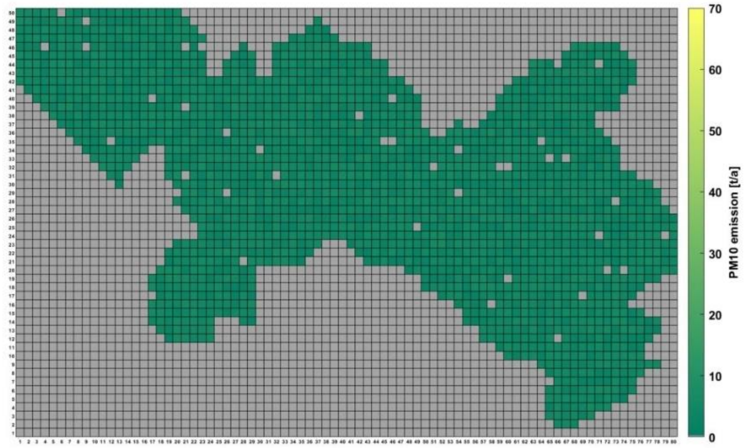


Figure 4.19. *CO_2 emission maps for the BC no. 4 for:* ***A)*** ***V0**, **B)** **V2*** *and* ***C)*** ***V8*** *scenarios*

A)



B)



C)

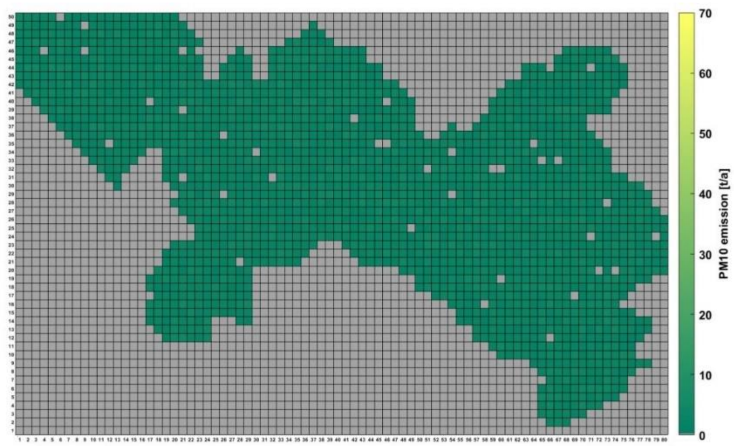


Figure 4.20. *PM_{10} emission maps for the BC no. 4 for: **A)** **V0**, **B)** **V2** and **C)** **V8** scenarios*

Finally, the energy-related summary is shown in **Table 4.18**. The chart shows the comparison between the base (**V0**) and modernized (**V8**) scenarios for heating and electricity demands and GHG emissions.

Table 4.18. *An energy-related summary for the BC no. 4*

	BASE	**MODERNIZED**
H_{TOTAL} [MWh/a]	42 419.93	N/A
H_{PEAK} [MW]	26.58	N/A
E_{TOTAL} [MWh/a]	21 181.60	9 991.28
E_{PEAK} [MW]	6.24	4.17
CO_2 [t/a]	18 685.00	2 847.62
SO_2 [t/a]	223.94	52.03
NO_x [t/a]	15.93	2.39
$PM_{2.5}$ [t/a]	41.74	4.92
PM_{10} [t/a]	53.73	6.36

Where: **H_{TOTAL}** – total heating demand; **H_{PEAK}** – peak heating demand; **E_{TOTAL}** – total electricity demand; **E_{PEAK}** – peak electricity demand

CONCLUDING REMARKS

This example showed, that it is possible to define a non-uniform building area (in terms of its shape and building types distribution) by means of the *TEAC* software. Those type of studies proved, that the developed tool is capable to analyse the actual residential areas. For this purpose, all available results options of the *TEAC* software are presented and discussed. Once again it was shown, that the Polish household sector has a huge potential in terms of energy and environmental improvements. Also, financial profitability is analysed in this work for all the proposed modernization scenarios.

5. APPLICATION OF THE *TEAC* SOFTWARE FOR SOME ENERGY FLEXIBLE BUILDING CLUSTER ANALYSES – CASE STUDIES

In this section, an application of the *TEAC* software for some case-study analyses is presented. Two residential neighbourhoods are examined; both of them are located in Lodz. Case no. 1 (described in section **5.1**) is a typical, small residential neighbourhood within the city district – it is a part of the *Smulsko* region. Case no. 2 (see more in section **5.2**), the so-called *Nowosolna* neighbourhood, can be considered as a suburban area, where single-family houses are a majority of all buildings. The both cases are defined using the satellite view of the selected areas, as well as data from the Polish Geoportal [410], launched by the *Head Office of Geodesy and Cartography* (in Polish: ***G****łówny* ***U****rząd* ***G****eodezji* ***i*** ***K****artografii*, GUGiK) [411]. The geoportal might be considered as the GIS database of Poland. Additionally, the buildings' distribution is assumed based on the statistical information from the GUS database, following the construction periods of the predefined types of RSFH of Poland (see **Table 5.1**). In the examined areas the streets pattern is not included, nevertheless, whenever it is possible their actual positioning is used to define buildings orientation – it is assumed that the front of each building always faced the street.

Table 5.1. *Statistic share of single-family houses of Poland based on their construction periods (source: [420])*

TYPE	CONSTRUCTION PERIOD	SHARE [%]
RSFH_1	BEFORE 1945	21.60
RSFH_2	1946-1966	22.50
RSFH_3	1967-1985	22.90
RSFH_4	1986-1992	7.90
RSFH_5	1993-2002	14.50
RSFH_6	2003-2008	5.30
RSFH_7	AFTER 2008	5.30

There are two main goals of the studies presented in chapter **5**. The first one has been already introduced – is it possible, to define and analyse the actual Polish residential neighbourhoods using the *TEAC* software. The second target is to analyse the transformation of the selected areas following the EFBC concept. Thus, it is necessary to propose some buildings modernization to improve their energy standards as well as provide the energy flexibility of the whole region. All buildings in the considered zones are assumed to be modernized to high energy-efficient standards. Moreover, the proposed modernizations aimed to transform all buildings to be fully supplied only with electricity – the heating is performed using GHPs and each house has a PV system. Application of highly efficient GHPs, excellent thermal insulation of buildings' enclosure, as well as electricity production out of PVs ensured, that the both examined areas consisted of houses, which are at least in NZEB standard. Energy flexible buildings are a basis to establish the EFBC – the above is possible if we add the energy storage systems to buildings. Batteries can significantly improve the local grid effectiveness and safety; because it makes possible to manage the load, as well as peak demands. These strategies increase local grid safety, as well as provide energy-independency for the examined area. To sum up, the neighbourhood consisting of highly energy-efficient houses, which use RES to produce and batteries to store and manage electricity is considered as EFBC, which is arguably the most advanced approach to create sustainable urban areas.

In order to perform the above-introduced study, it is necessary to include the comprehensive analysis of electricity costs for the defined EFBCs. The economic calculations are performed using the actual prices and energy-tariffs from the local operator in Lodz. The performed study is also following the newest Polish regulations, published in 2017 [345], following the information announced in late 2020. The above-mentioned announcement introduced the new tax system (valid from 1st January 2021), influencing the electricity prices for both residential and non-residential consumers. The main goal of the new charge is to provide national energy safety, as well as to minimize extreme events such as blackouts. The gathered funds will be transferred to the national electricity operators for the maintenance, modernization, as well as development of power plant units in Poland. The additional charge is defined differently for the residential and non-residential buildings. For the residential buildings, the fee depends on the annual electricity consumption, as follows:

- **RF1** – lower than 0.5 MWh/a: 1.87 PLN/month,
- **RF2** – between 0.5-1.2 MWh/a: 4.48 PLN/month,
- **RF3** – between 1.2-2.8 MWh/a: 7.47 PLN/month,
- **RF4** – above 2.8 MWh/a: 10.46 PLN/month.

For the non-residential buildings, it is applied as an additional cost of 0.0762 PLN/kWh during peak hours, from 7:00 AM till 10:00 PM every workday. The schema of the new pricing system for non-residential buildings can be seen in **Figure 5.1**.

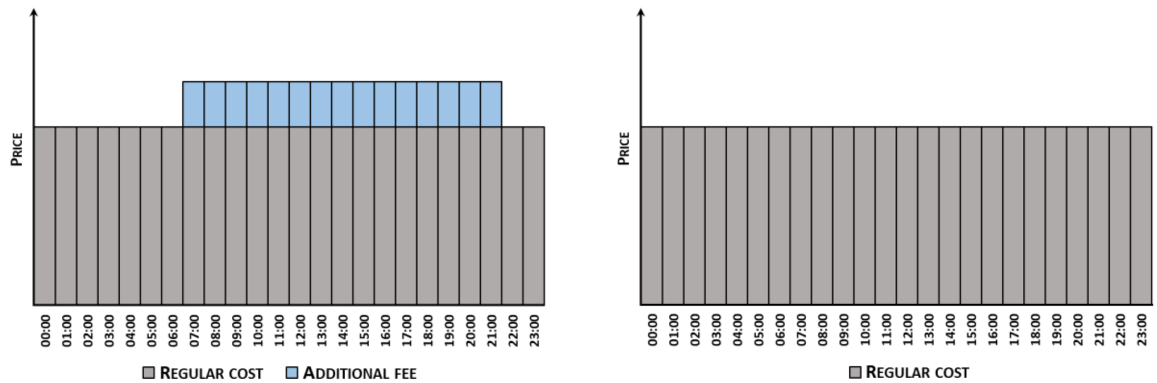


Figure 5.1. *New electricity pricing for the non-residential buildings workdays (on left) and weekends (on right)*

Also, to maximize financial profits, it is necessary to select the most beneficial tariff out of the ones proposed by the operator. In the performed analysis two approaches will be considered. The first one assumed, that each building out of the examined neighbourhood settles up individually, while the second one considered the whole examined BC as a single unit. The second approach is fully adequate considering the definition of the EC (see more in section **2.6**). Therefore, in this chapter both scenarios are compared, using the tariffs published by local electricity distributor.

The first set of tariffs, valid only for residential buildings, is assigned with G. The G11 charge assumes the constant electricity price 24/7; the cost is set for 0.2107 PLN/kWh. The G12 is the so-called '*day & night*' tariff – it assumes higher pricing during predefined day-hours and lower cost of electricity during the night-time. The higher price is set as 0.2462 PLN/kWh while the lower one at 0.0723 PLN/kWh. The last tariff, G12w is a so-called '*weekend*' fare; it has higher electricity cost during selected periods of the weekdays, while lower price occurs during weekends and remaining time during the workdays. The higher price is set as 0.2561 PLN/kWh, while the lower one at 0.0689 PLN/kWh. Graphical schemas of the G-type tariffs are shown in **Figure 5.*2***. It is also important to add the additional fee (introduced earlier in this chapter), depending on the annual electricity consumption. Moreover, it is obligated to add the charge based on peak power demand; it is included each month and the cost is set to 8.5 PLN/kW.

The second considered a set of tariffs is valid for enterprises and it is assigned with symbol C. For the examined scenarios, the group of C2 tariffs is selected – it operates companies with a peak demand of over 40 kW. The C21 is similar to the G11 tariff – it assumes the constant electricity price set for 0.1407 PLN/kW. The C22a is the so-called '*peak hours*' tariff, it has selected daytimes when electricity is more expensive. Moreover, those periods are defined for each month, as shown in **Table 5.2**. The C22b is similar to the G12 tariff – it has a higher electricity price during the predefined daytimes. The electricity prices are 0.1673 PLN/kWh during the day and 0.0549 PLN/kWh during the night. The C23 tariff includes three different pricing zones, depending on the daytime. In this fare, electricity consumption during peak hours is the most expensive (0.2207 PLN/kWh), during the pre-peak hours it costs 0.1559 PLN/kWh and 0.0526 PLN/kWh for the rest of the time. The important fact is that peak and pre-peak hours occur only during weekdays, as well as that peak hours are different during summer and winter; the heating season is set from 1st October till 31th March. Graphical schemas of the C-type tariffs are shown in **Figure 5.3.** Additionally, the new additional fee for the non-residential buildings (see **Figure 5.1**) should be added for the examined BC, during predefined peak hours. The last fee relates to the peak power demand for each C-type tariff; the additional cost is included every month based on the maximal power demand, as follows:

- 15.14 PLN/kW for C21,
- 15.71 PLN/kW for C22a and C22b,
- 16.75 PLN/kW for C23

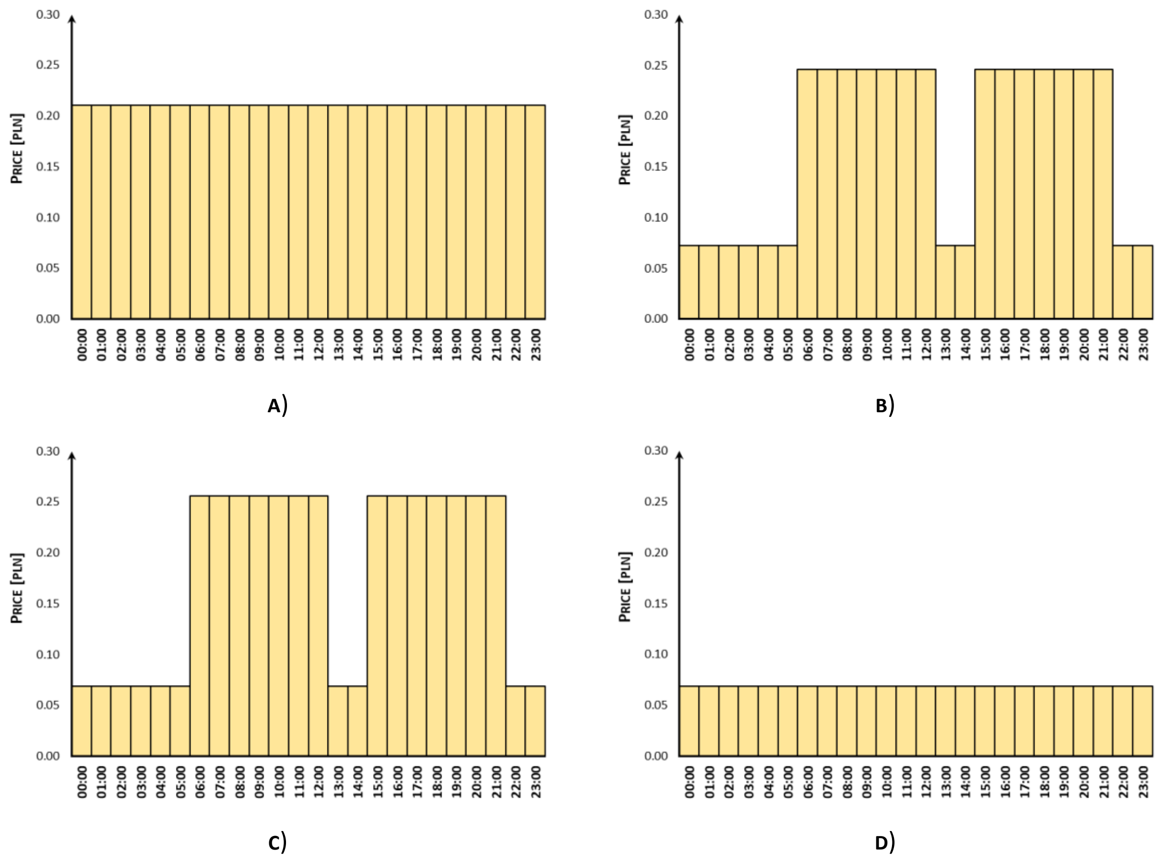
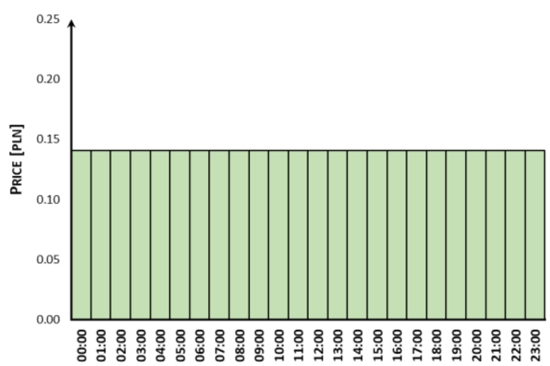


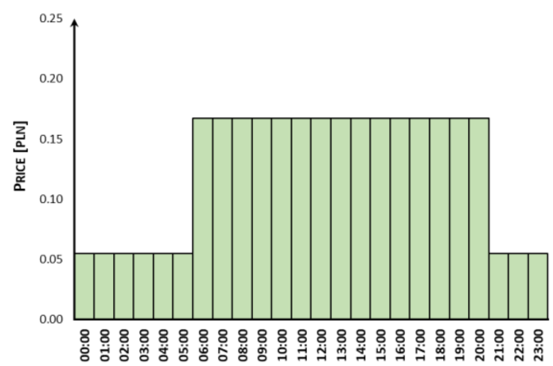
Figure 5.2. *Schemas of the G-type tariffs: a) G11, b) G12, c) G12w weekdays, d) G12w weekends*

Table 5.2. *Time zones valid for the C22a tariff*

MONTH	PEAK HOURS	OFF-PEAK HOURS
JANUARY	8:00-11:00 AM, 4:00-9:00 PM	11:00 AM – 4:00 PM, 9:00PM – 8:00 AM
FEBRUARY	8:00-11:00 AM, 4:00-9:00 PM	11:00 AM – 4:00 PM, 9:00PM – 8:00 AM
MARCH	8:00-11:00 AM, 6:00-9:00 PM	11:00 AM – 6:00 PM, 9:00PM – 8:00 AM
APRIL	8:00-11:00 AM, 7:00-9:00 PM	11:00 AM – 7:00 PM, 9:00PM – 8:00 AM
MAY	8:00-11:00 AM, 8:00-9:00 PM	11:00 AM – 8:00 PM, 9:00PM – 8:00 AM
JUNE	8:00-11:00 AM, 8:00-9:00 PM	11:00 AM – 8:00 PM, 9:00PM – 8:00 AM
JULY	8:00-11:00 AM, 8:00-9:00 PM	11:00 AM – 8:00 PM, 9:00PM – 8:00 AM
AUGUST	8:00-11:00 AM, 8:00-9:00 PM	11:00 AM – 8:00 PM, 9:00PM – 8:00 AM
SEPTEMBER	8:00-11:00 AM, 7:00-9:00 PM	11:00 AM – 7:00 PM, 9:00PM – 8:00 AM
OCTOBER	8:00-11:00 AM, 6:00-9:00 PM	11:00 AM – 6:00 PM, 9:00PM – 8:00 AM
NOVEMBER	8:00-11:00 AM, 4:00-9:00 PM	11:00 AM – 4:00 PM, 9:00PM – 8:00 AM
DECEMBER	8:00-11:00 AM, 4:00-9:00 PM	11:00 AM – 4:00 PM, 9:00PM – 8:00 AM



A)



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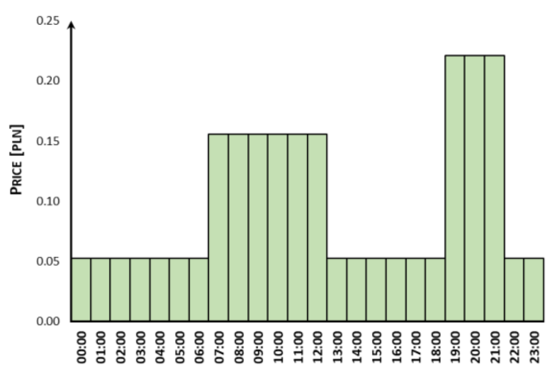

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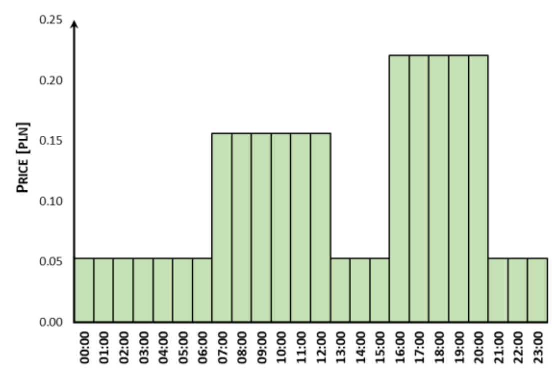

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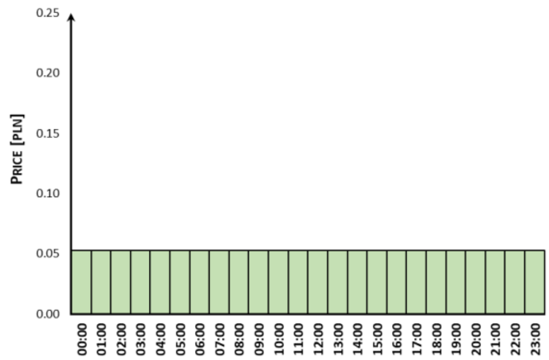


E)

Figure 5.3. *Schemas of the C-type tariffs: A) C21, B) C22b, C) C23 for weekdays during summer, D) C23 for weekdays during winter, E) C23 for weekends*

As it was already explained (see more in section **2.4**), whenever we are using RES (especially PVs) it is necessary to decide, if our system includes energy storage (so-called ‘*off-grid*’ or ‘*hybrid*’ technology) or not (‘*on-grid*’ schema). Whenever the applied system is connected to the grid a homeowner is considered as a prosumer, which is introduced in [339] and [345]; the phrase came from the words **pro**ducer and con**sumer**. The prosumer strategy is possible because of the ‘*net-metering*’ mechanism, which is based on balancing energy consumption and introducing surpluses to the grid. The ‘*net-metering*’ mechanism allows consumers to use the grid as a sort of energy storage. The prosumer policy provides the necessary information on how the electricity transfer is done; the regulations are different for residential buildings and enterprises, as well as they depend on the system rating, expressed with its’ peak performance. For individual residential buildings, the maximally allowed system rating is 50 kW, and rebates are as follows:

- system peak power < 10kW: compensation equal to 80% of the electricity transferred to the grid,
- system peak power > 10kW: compensation equal to 70% of the electricity transferred to the grid.

According to the prosumer rules, it is also possible to perform electricity transfer to the grid based on the so-called ‘*prosumer bundle*’, which, according to [339], is highly recommended for units like EC. The ‘*prosumer bundle*’ is a strategy defined to promote RES applications for non-residential consumers. The ‘*prosumer bundle*’ mechanism allows to connect micro-systems, which combine rating is lower than 10 MWp. If the above-mentioned requirements are met, then the examined EC can transfer the electricity to the grid with the compensation index equal to 0.6.

Based on the above-introduced overview of the electricity pricing in Poland it seems obvious that it is necessary to compare, which way of reckoning is more profitable for areas considered as EC. In practice, it is possible to assume, that the examined EC consisted of multiple individual consumers, or considered the whole neighbourhood as a single unit. The first approach has a higher electricity price, but it has a much lower cost of the ordered design power compering with tariffs recommended for non-residential consumers. Also, the prosumer mechanism is more beneficial for individual clients. Therefore, it is important to calculate, which aspect is more financially influential for the examined neighbourhood: is its electricity consumption, power demand or energy compensation rate from RES applications.

Additionally, in this chapter, the application of batteries is examined. It is performed for two scenarios: the first one is based on the commercially available batteries, while the second one examined the hypothetical energy storage, which is capable to store all the produced electricity out of RES. The batteries application might be applied as individual units, for each building within the examined neighbourhood, or as a single large element for the whole EC. The usage of the energy storages maximize the RES potential; batteries might be more beneficial comparing with the available prosumer mechanism (energy compensations). The energy storage systems are furtherly introduced in section **2.4**. Some popular commercially available batteries for building applications are presented in **Table 5.3**; in further analyses, the *PylonTech Force L2* battery is used. This model is selected based on the price-to-capacity ratio, as well as its availability in Europe.

Table 5.3. *Technical parameters of some commercially available batteries*

#	MODEL	TYPE	CAPACITY [kWh]	PEAK POWER [kW]	PRICE [PLN]
1	*PYLONTECH FORCE L2*	LFP *	10.65	5.0	22 800
2	*LG 51V*	LI-ION **	10.00	5.0	27 300
3	*VARTA PULSE NEO 6*	LI-ION **	5.85	2.3	26 999
4	*TESLA POWERWALL 2*	LI-ION **	13.50	5.0	26 500

Where: ***** – lithium iron phosphate (so-called lithium ferrophosphate) battery; ****** – lithium-ion battery

As it can be seen, the cost of house energy storage system is rather high. Despite the fact of advantageous features of batteries for energy management and transition, it is difficult to obtain financial profitability out of their application. Nevertheless, according to numerous forecasts and scientific reports, it is shown, that energy storage technology is developing rapidly. The above-mentioned indicates, that batteries performance will increase while their price will decrease in the nearest future. According to [297], by 2030 the price of the Li-ion system might decrease by up to 70 % comparing with the average price in 2016 (the cost for stationary applications could fall below 200 USD/kWh). Therefore, studies with the application of energy storages are extremely important and should be performed nowadays, in order to predict potential energy benefits. The above-mentioned is even more important if we bring up the rapid development of PV technology. The PV installations are constantly more and more efficient, cheaper and their number increase significantly every year. Assuming, that batteries are usually a part of PV systems it seems just a matter of time when we will witness the breakthrough in the attractiveness (both energy and economic) of this technology.

Finally, all the above mentioned provides the flexibility of the local electricity grid. The application of PV systems with batteries allows for application of technologically advanced DSM strategy (see more in section **2.4**). This active method is highly focused on peak clipping, load shifting, as well as stable energy demand. The schema of the considered mechanism is presented in **Figure 2.28**. Application of those type of active DSM techniques might result in well managed and highly efficient EFBC. The studies presented in this chapter are focused on energy safety, flexibility and independence of the examined residential neighbourhoods.

To implement all the above-mentioned mechanisms into some EFBC analyses, the complex method of active demand management is required. The PVs system with batteries required some kind of smart metering monitoring, while to compare the electricity bills for different tariffs a cost calculator is needed. Therefore, an extension of the *TEAC* software is defined using the datasheet in the *Excel* software. The defined calculator should be rather considered as a post-processing of the results obtained out of the *TEAC* software. At this moment that spreadsheet is not considered as a stand-alone module (or submodule) of the *TEAC* software, therefore its' description is not included in section **3.7**. The applied smart metering method, valid for scenarios with PVs and batteries application is introduced below.

All the steps performed in the defined calculator are based on the results obtained from the *TEAC* software – the hourly electricity demand, as well as the hourly electricity production out of PVs for each building out of the examined BC is required. The electricity produced out of PVs can be used right away, stored in the batteries or sold (following the prosumer mechanism) to the grid. The method of the immediate use of the electricity produced out of PVs is the same as it is defined in the solar module (see more in submodule **3.7.4**). Then, the batteries are counted to store as much of the surplus electricity for the PVs as possible. It can be performed assuming the infinite storage or one of the commercially available batteries (some are shown in **Table 5.*3***). For the scenario with infinite storage, an '*off-grid*' system is considered, while for the actual batteries the hybrid system is assumed (see more in section **2.4**). Whenever the hybrid mechanism is used, an extra amount of electricity (quantity, which was either used immediately or stored) is settled following the prosumer regulations. Additionally, this solution assumed discharge of the majority of battery capacity during evenings, while 20 % of the daily reserves are kept to be used for the next day morning peak clipping. Finally, the amount of electricity, which is traded to the grid and then received back as compensation is proportionally decomposed over the highest demands. For an '*off-grid*' scenarios, all the surplus electricity out of the PV systems is used for the local load management. The stored electricity is used equivalently to manage hourly demands (peak clipping and load shifting). The schemas of the electricity demand management mechanisms are shown in **Figure 5.4**.

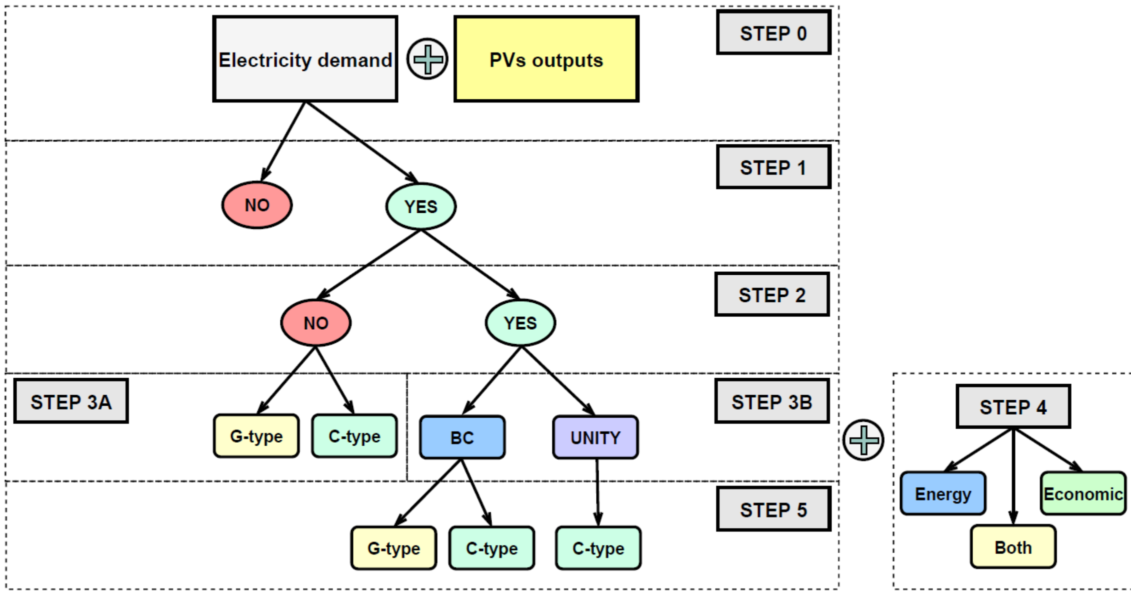


Figure 5.4. *Schema of the smart-metering technique used in the TEAC software*

Moreover, two electricity pricing approaches might be examined, accordingly for residential and non-residential (enterprises) consumers. In the defined calculator it is possible to determine the main goal of the performed analysis – it might be focused on either the economic (the most profitable billing) or energy (electricity load management and peak clipping) aspect. The energy aspect is recommended especially for tariffs with the constant price, such as G11 or C21. Additionally, it is possible to use the defined calculator to perform some economic analyses of the BC, based just on the electricity pricing – it can be achieved assuming a battery system with a zero capacity.

5.1. CASE NO. 1 – *SMULSKO* NEIGHBOURHOOD

In this section, a small residential area is examined, in order to transform the actual BC into EFBC. The examined zone is located in Lodz – it is a small part of a residential neighbourhood called *Smulsko*. The satellite view of the examined area can be seen in **Figure 5.5**. In order to define this area in the *TEAC* software, some pre-processing actions are required. Basically, it is necessary to adjust a given image to the predefined grid, which is used in the *TEAC* software for area definition purposes. When it is done, the arrangement of the proper buildings is performed by overlapping the grid on the satellite view of the examined area. Whenever a building image fits within a cell, thus a parcel is occupied. Finally, buildings orientation are assumed, considering the already performed rotation of the examined zone – in this example the original image has been rotated by 45 degrees counter-clockwise (see **Figure 5.6** on left). Additionally, buildings placement is performed following statistical data (see **Table 5.1**); the schema of the examined BC is shown in **Figure 5.6** (on right). The analysed area is a square-based zone, 23 by 23 parcels; 202 houses constituting the examined BCFigure 5.6. The examined BC no. 5: preparation (on left) and the final schema (on right)

Table 5.4; their orientations are assumed randomly.

Figure 5.5. *The satellite view of the examined BC no. 5 – Smulsko neighbourhood*

Some modernization variants are proposed in order to transform this residential area into EFBC. The first step assumed buildings refurbishment, GHP application, as well as lighting system modernization – then the examined BC is transformed to be supplied only by electricity. After that more advanced strategies can be applied, such as RES (using '*standard*' PVs use) and batteries application, as well as usage of smart metering techniques. The following scenarios are considered:

- **V0** – the base scenario,
- **V1** – buildings refurbishment following the BRV_2 scenario,
- **V2** – application of GHP (HV_2 scenario) after the **V1** modernization,
- **V3** - replacement of traditional lightbulbs with LEDs,
- **V4** – scenarios **V2** and **V3** simultaneously,
- **V5** – application of PVs into the **V4** scenario (without batteries),
- **V6** – application of PVs into the **V4** scenario with an energy storage system and usage of smart metering techniques (each building is a unique prosumer).

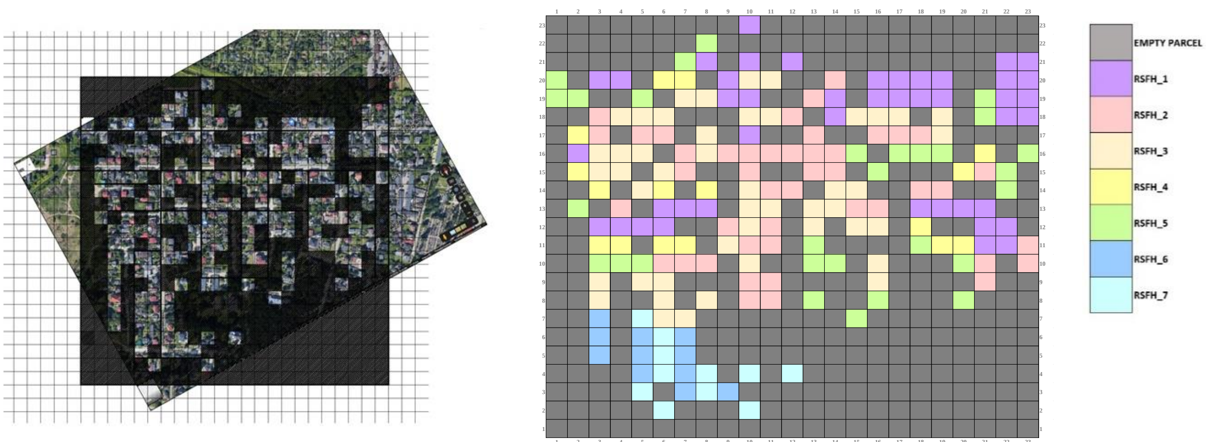


Figure 5.6. *The examined BC no. 5: preparation (on left) and the final schema (on right)*

Table 5.4. *Buildings distribution summary for the BC no. 5 – Smulsko neighbourhood*

BUILDING TYPE	**NUMBER**	$A_{o,tot}$ [m^2]	$A_{roof,total}$ [m^2]	$A_{roof,avail}$ [m^2]
RSFH_1	44	3 471.60	1 848.00	1 176.00
RSFH_2	45	4 464.00	2 587.50	1 466.25
RSFH_3	46	6 178.26	3 542.00	2 310.00
RSFH_4	16	2 238.72	1 280.00	800.00
RSFH_5	29	4 498.48	2 610.00	1 575.00
RSFH_6	11	1 892.44	1 116.50	812.00
RSFH_7	11	2 073.39	1 210.00	715.00
TOTAL	202	24 816.89	14 194.00	8 854.25

<u>Where</u>: $A_{o,tot}$ – total occupied area; $A_{roof,total}$ – total roof area; $A_{roof,avail}$ – available roof area (appropriate for PVs)

Some results presented by means of maps are shown in **Figure 5.7**. It is hard to compare heating and electricity demands because the most comprehensive modernizations are supplied with electricity only. Therefore, a comparison of CO_2 emissions is presented – the results always show the total amount of emitted pollutants (the sum from heating and electricity). The base case (**V0**) is compared with the **V6** scenario. All the proposed modernizations improve local environmental protection.

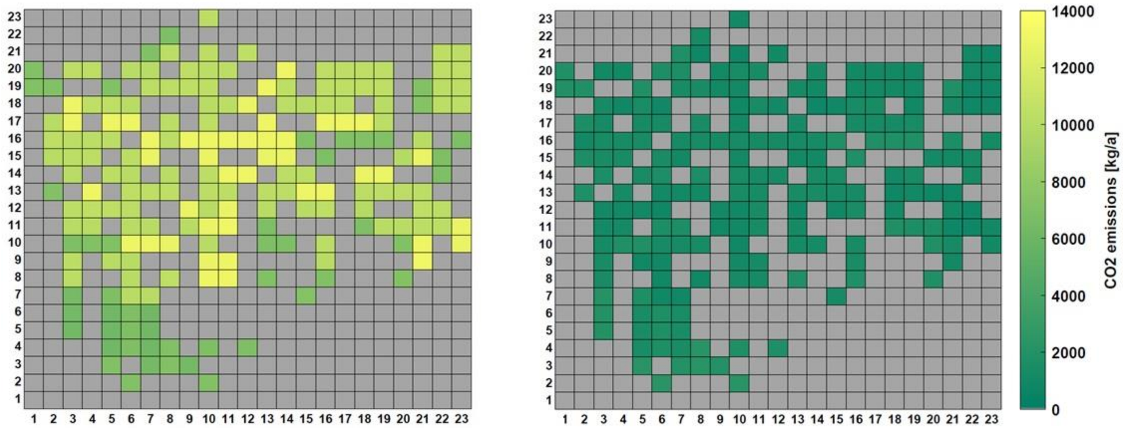


Figure 5.7. *CO_2 emission maps for the BC no. 5 for the base (on left) and the V6 (on right) scenarios*

All the examined variants are compared in **Table 5.5**, showing the energy demand summary. It can be seen, that traditional modernization (the **V4** scenario) reduced the total energy demand of the examined area; it included electricity demand for heating purposes and still, the total energy amount is lower by approx. 18 % compared with the base scenario. More advanced strategies furtherly reduced the energy demand, by up to 49 % (for the **V6** case), as well as peak demand, by approx. 35 % (for the **V5** scenario).

Table 5.5. *Energy consumption summary for the BC no. 5 – Smulsko neighbourhood*

VARIANT	H_{TOTAL} [MWh/a]	H_{PEAK} [kW]	E_{TOTAL} [MWh/a]	E_{PEAK} [kW]
V0	4 913.76	3 050.77	1 895.19	556.84
V1	867.44	554.22	N/A	N/A
V2*	256.33	165.21	N/A	N/A
V3	N/A	N/A	1 301.76	337.18
V4	N/A	N/A	1 558.08	470.47
V5	N/A	N/A	988.54	363.96
V6	N/A	N/A	965.64	465.46

Where: **H_{TOTAL}** – total heating demand; **H_{PEAK}** – peak heating demand; **E_{TOTAL}** – total electricity demand; **E_{PEAK}** – peak electricity demand; ***** in this variant heating is performed using electricity

Electricity LDCs are shown in **Figure 5.8**. It can be seen, that all the proposed modernizations improved safety of the local grid. The electricity demand is more uniform, with lower peak demands. Additionally, the proposed techniques in the **V6** variant provided temporal energy-independency of the examined area – the zeroth electricity demand is observed for as long as 1388 h.

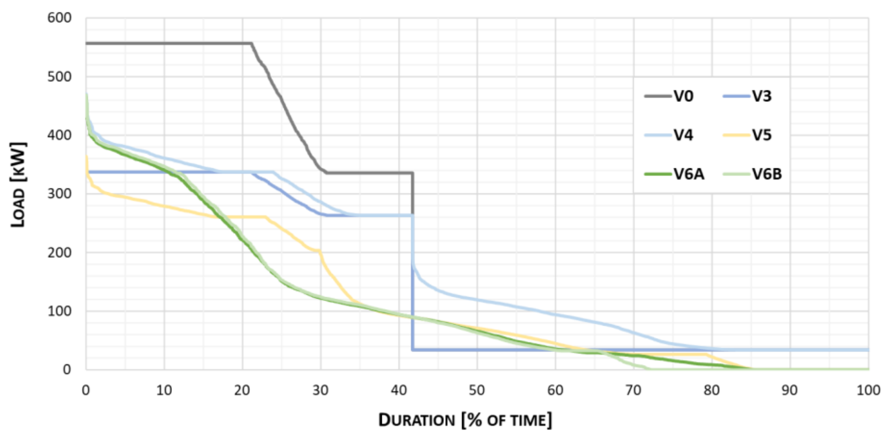


Figure 5.8. *Electricity LDCs for BC no. 5 – Smulsko neighbourhood*

The simultaneous application of PVs and batteries allows transforming the examined BC into EFBC. It is possible to manage the electricity demand depending on our needs and goals. The aims can be focused on energy consumption reduction or cheaper billing. The smart metering method is assumed, that each building within the examined BC is a prosumer; therefore, the surplus amount of electricity can be used later, in more crucial moments (*i.e.* when peak demand is observed). The analysis is performed for two scenarios, accordingly for each building individually, or the whole BC as a unity. Hence different regulations and electricity pricing are applied depending on the selected scenario (see more in chapter **5**). The comparison between the above-mentioned scenarios (assigned accordingly as **V6A** and **V6B**) and the **V5** variant is shown in **Table 5.6**. The **V6B** variant is the best in terms of energy savings, while surprisingly the **V5** scenario reduces peak demand the most. The unexpected results are caused due to the calculation methods used in different modules of the *TEAC* software. If only PVs are applied, it is assumed that the surplus amount of electricity is then proportionally distributed, depending on the given demand (see more in subsection **3.7.4**). Whenever batteries are involved, their potential is analysed day-by-day, in order to ensure a capacity for the upcoming day. The first approach can be considered as rather hypothetical, while the second one is much more practical. Additionally, the **V6B** scenario provided a total reduction of electricity consumption (zeroth demand) for more than a quarter of the year (approximately 2450 h).

Table 5.6. *Energy consumption summary for the BC no. 5 – Smulsko neighbourhood*

VARIANT	E_{TOTAL} [MWh/a]	E_{PEAK} [kW]	*0-TIME* [%]
V5	988.54	363.96	14.05
V6A	965.64	465.46	15.83
V6B	959.97	468.69	27.98

Where: E_{TOTAL} – total electricity demand; E_{PEAK} – peak electricity demand; ***0-TIME*** – a sum of the time with zeroth electricity consumption

The economic analysis is performed based on the selection of most appropriate electricity billing tariff. It is important to mention, that those type of financial savings are obtained without (or with minimal) initial costs – it requires a change of electricity pricelist only. The obtained costs are compared with the ones for a typical tariff, so-called '*all-day*', accordingly G11 or C21; thus it is possible to see the potential savings. Additionally, the comparison can be performed for different modernization variants. The energy costs for different pricing and scenarios are shown in **Table 5.7**. It can be seen, that it is possible to generate saving within each variant, only by switching the tariff. The highest observed difference within the single scenario (in this case the **V4**) is equal to 33 %, while the potential financial savings can reach 202 516.80 PLN/a.

Table 5.7. *Electricity costs summary for the BC no. 5 – Smulsko neighbourhood*

TARIFFS	**TOTAL COST** [PLN/a]			
	V4	**V5**	**V6A**	**V6B**
G11	387 341.10	253 969.48	261 884.03	261 096.08
G12	382 396.01	249 684.75	250 943.07	248 860.76
G12W	312 491.97	210 010.11	205 087.24	203 206.32
C21	304 696.71	205 211.27	220 429.82	220 219.35
C22A	348 576.94	233 795.56	251 788.27	251 451.54
C22B	306 727.38	201 031.22	214 946.70	213 887.95
C23	259 309.28	184 824.30	199 260.80	199 062.40

Finally, the energy-related summary is shown. The comparison between the base (**V0**) and modernized (**V6B**) scenarios for heating and electricity demands, as well as GHG emissions, is shown in **Table 5.8**. A significant improvement in terms of energy demand, as well as environmental protection, are obtained.

Table 5.8. *An energy-related summary for the BC no. 5 – Smulsko neighbourhood*

	BASE	MODERNIZED
H_{TOTAL} [MWh/a]	4 913.76	N/A
H_{PEAK} [kW]	3 050.77	N/A
E_{TOTAL} [MWh/a]	1 895.19	959.97
E_{PEAK} [kW]	556.84	468.69
CO_2 [t/a]	2 032.16	272.89
SO_2 [t/a]	27.21	4.99
NO_x [t/a]	1.72	0.23
$PM_{2.5}$ [t/a]	5.63	0.47
PM_{10} [t/a]	7.27	0.61

Where: **H_{TOTAL}** – total heating demand; **H_{PEAK}** – peak heating demand; **E_{TOTAL}** – total electricity demand; **E_{PEAK}** – peak electricity demand

CONCLUDING REMARKS

This example had two main purposes. The first one was to check if it is possible to define the actual residential area, based on the satellite image using the *TEAC* software. It was shown, that it is possible, but requires some pre-processing of the selected area image. The second goal was to perform a study, that proves if the *TEAC* software is a suitable tool for various EFBC analyses. Based on the obtained results it can be concluded, that the defined software can be used in studies focusing on areas considered as EFBC. It is possible to examine the potential profitability of some advanced energy management strategies, such as PVs or batteries usage, as well as the application of active DSM techniques. Additionally, it is possible to obtain a valuable financial analysis for different electricity tariffs. Those type of studies might be helpful for the local authorities or the government to significantly improve the energy and environmental characteristics of the examined residential area, with potentially major financial benefits.

5.2. CASE NO. 2 – *NOWOSOLNA* NEIGHBOURHOOD

In this section, another residential area is examined in order to check its availability to became an EFBC. The performed study is similar to the one presented in section **5.1**, but for a much larger region. The examined zone is located in Lodz; it is the so-called *Nowosolna* neighbourhood. It is a typical suburban residential region, approx. 12 kilometres from the city centre. It is a very interesting area in terms of its unusuality; its central point is an 8 streets crossing. As it was already mentioned, the examined residential area is spread over a large area; the considered region is a rectangle, 2700 m by 3900 m (approx. 1053 ha of land). The satellite view of the analysed region is shown in **Figure 5.9**.

Figure 5.9. *The satellite view of the examined BC no. 6 – the Nowosolna neighbourhood*

Similarly as in the previous example, the satellite view is used in order to define the examined BC. In this case, the image was rotated only by approx. 7 degrees counter-clockwise to fit the streets pattern with the predefined parcels grid. Due to the fact, that the orientation impact in the *TEAC* software varies by 45 degrees, the above-mentioned rotation by 7 degrees is negligible. Next, the buildings placement has been done, using an optical fitting. It can be seen, that buildings distribution is non-uniform, as well as rather irregular; the examined BC consists of 1098 single-family houses. The examined area involves 11.7 thousand parcels; only 9.4 % of them are occupied. It was assumed, that the centre of this region consists of public building; thus this part of the area was not analysed. Building types distribution is assumed following the national statistical data (see more in **Table 5.1**) and their orientation is random. The schema of the examined BC can be seen in **Figure 5.10** and the buildings distribution summary is shown in **Table 5.9**.

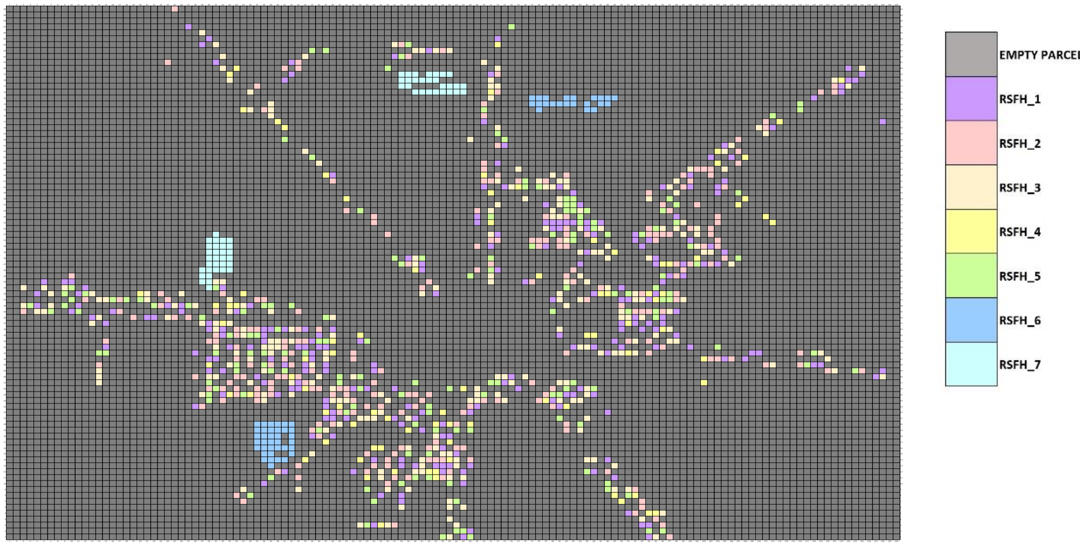


Figure 5.10. *Schema of the analysed area – BC no. 6 – the Nowosolna neighbourhood*

Table 5.9. *Building types distribution summary for the BC no. 6 – the Nowosolna neighbourhood*

BUILDING TYPE	NUMBER	$A_{o,tot}$ [m²]	$A_{roof,total}$ [m²]	$A_{roof,avail}$ [m²]
RSFH_1	238	18 778.20	9 996.00	6 279.00
RSFH_2	247	24 502.40	14 202.50	9 257.50
RSFH_3	251	33 711.81	19 327.00	12 089.00
RSFH_4	87	12 173.04	6 960.00	4 400.00
RSFH_5	159	24 664.08	14 310.00	8 685.00
RSFH_6	58	9 978.32	5 887.00	3 704.75
RSFH_7	58	10 932.42	6 380.00	4 290.00
TOTAL	1 098	134 740.27	77 062.50	48 705.25

Where: $A_{o,tot}$ – total occupied area; $A_{roof,total}$ – total roof area; $A_{roof,avail}$ – available roof area (appropriate for PVs)

In this example, the following scenarios are analysed:

- **V0** – base scenario,
- **V1** – buildings refurbishment (BRV_3) with GHPs application (HV_2),
- **V2** – application of PVs into the **V1** scenario,
- **V3A** – the **V2** scenario with batteries,
- **V3B** – the **V2** scenario with infinite electricity storage.

The above-mentioned modernizations allow to transform this traditional area into a highly energy-efficient and environmentally friendly EFBC. The applied PVs are assumed to be highly-efficient ones, with the efficiency of 21 % (280 Wp each). The total area of 25 028.85 m² PVs can produce up to 3 433.12 MWh/a electricity, with a peak productivity of 4.19 MWp. Additionally, the usage of energy storage systems is considered in order to manage the electricity demand of the region. Application of the batteries is considered for two scenarios: assuming a single energy-bank (with the capacity of 10.65 kWh) to each house (the **V3A** scenario), as well as assuming infinite storage (**V3B**) for the whole BC.

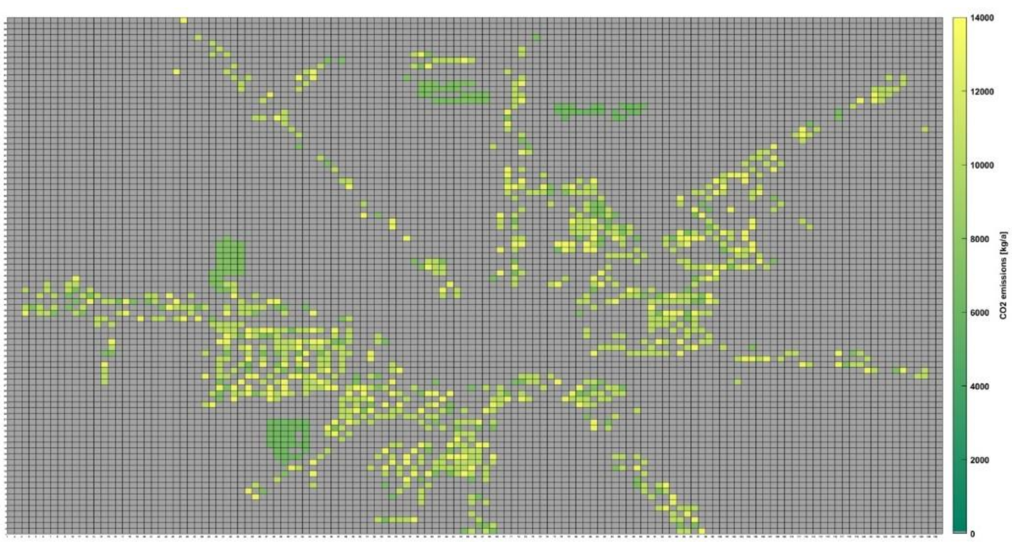
The performed calculations are summarized in **Table 5.10**. Out of the examined scenarios, the **V3B** variant is the most profitable in terms of energy consumption reduction. Also, it is the most environmentally friendly – the emissions are decreased by an average of approx. 90 %. The comparison of CO_2 emissions maps between the base (**V0**) and **V3B** scenarios is shown in **Figure 5.11**. A significant energy and environmental improvement of the region is observed.

Table 5.10. *An energy- and environmental-related summary for the BC no. 6 – the Nowosolna neighbourhood*

	V0	**V1**	**V2**	**V3A**	**V3B**
H_{TOTAL} [MWh/a]	26 861.42	N/A	N/A	N/A	N/A
H_{PEAK} [MW]	16.68	N/A	N/A	N/A	N/A
E_{TOTAL} [MWh/a]	10 300.14	7 733.23	4 548.66	4 426.99	4 178.43
E_{PEAK} [MW]	3.03	2.18	1.58	2.15	2.06
CO_2 [t/a]	11 092.15	2 204.05	1 296.42	1 261.74	1 190.90
SO_2 [t/a]	148.46	40.27	23.69	23.05	21.76
NO_x [t/a]	9.39	1.85	1.09	1.06	1.00
$PM_{2.5}$ [t/a]	30.78	3.81	2.24	2.18	2.06
PM_{10} [t/a]	39.73	4.92	2.89	2.82	2.66

Where: H_{TOTAL} – total heating demand; H_{PEAK} – peak heating demand; E_{TOTAL} – total electricity demand; E_{PEAK} – peak electricity demand

A)



B)

Figure 5.11. *CO_2 emission maps for the BC no. 6 for the following scenarios:* ***A)*** ***V0*** *and* ***B)*** ***V3B***

The above-discussed modernizations are financially beneficial, due to the fact of significant reductions in energy consumption. The potential profits might be even higher, whenever an appropriate electricity tariff is selected. The application of different charging schemas is examined, for the analysed neighbourhood. The obtained results are shown in **Table 5.11**; the comparison between the **V0**, **V1**, **V2** and both **V3** scenarios is performed (it includes electricity demand only). Due to the fact, that the **V3B** case assumes an infinite battery, therefore only C-type tariffs are considered for this scenario (the whole BC is considered as a unity). It is necessary to compare the obtained costs with the reference case; it is assumed, that costs obtained from G11 and C21 tariffs are representative. The most profitable tariff (for all examined variants) is the C23. The potential profits can be as high as 1 718 257.26 PLN/a – the difference between the **V0** scenario costing with G11 tariff and the **V3B** with C23. Within each variant, the potential savings can be as high as 355 272.49 PLN/a (for the **V1** scenario) – that type of modernization is obtained with marginal (or even without) initial costs. Moreover, the most expensive reckonings are observed for the base scenario, which did not include heating energy; thus the proposed estimates are even more promising.

Some interesting conclusions can be learnt from the comparison between **V3A** and **V3B** variants. It can be seen, that the '*infinite*' energy storage can fully use the amount of electricity generated by PV systems. Also, that approach will be more and more popular over the next years; it is profitable to design a single electricity-bank in order to manage the local demands. A short comparison performed with the best cases out of the obtained results, for the **V3A** and **V3B** scenarios is shown in **Table 5.12**. Not only the second scenario provided larger savings in electricity demand, but also it allows us to use the full potential of applied RES. Additionally, it provided a longer period of zeroth demand, as well it is more financially beneficial. Thus, those type of modernizations should be considered to design sustainable residential areas, especially in the nearest future. A collation of electricity LDCs for different scenarios is shown in **Figure 5.12** – it is another approach to energy transformation of the examined neighbourhood.

Table 5.11. *Electricity costs summary for the BC no. 6 – the Nowosolna neighbourhood*

	TOTAL COST [PLN/a]				
TARIFFS	V0	V1	V2	V3A	V3B
G11	2 515 259.48	1 837 495.49	1 085 722.99	1 137 032.76	N/A
G12	2 623 310.88	1 847 433.85	1 090 394.70	1 112 151.55	N/A
G12W	2 108 703.47	1 482 223.00	900 328.06	881 814.99	N/A
C21	1 999 195.04	1 483 725.22	927 298.31	1 038 232.25	954 417.02
C22A	2 353 672.22	1 711 038.12	1 067 340.14	1 203 610.77	1 034 629.08
C22B	2 061 968.46	1 508 568.68	917 017.66	1 009 761.27	914 900.06
C23	1 794 234.28	1 268 485.57	845 961.14	920 476.41	797 002.22

Table 5.12. *A summary of batteries application for the BC no. 6 – the Nowosolna neighbourhood*

	V3A	V3B
E_{TOTAL} [MWh/a]	4 426.99	4 178.43
E_{PEAK} [MW]	2.15	2.06
$SOLAR_{USE}$ [MWh/a]	3 184.57	3 433.12
0-TIME [%]	16.6	17.7
$TOTAL_{cost}$ [PLN/a]	881 814.99	797 002.22

Where: E_{TOTAL} – total electricity demand; E_{PEAK} – peak electricity demand; $SOLAR_{USE}$ – the total amount of used electricity out of PVs; ***0-TIME*** – a sum of the time with zeroth electricity consumption

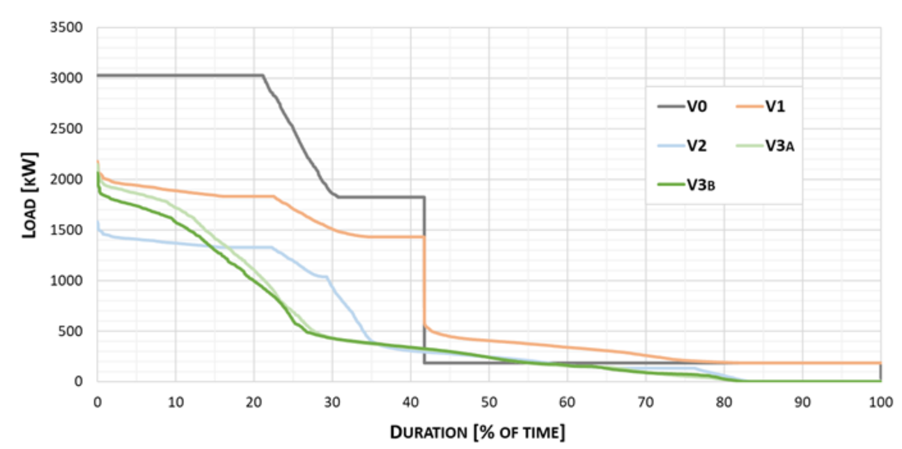


Figure 5.12. *Electricity LDCs for the BC no. 6 – the Nowosolna neighbourhood*

CONCLUDING REMARKS

In this example, a large residential area, which can be considered as BC, is examined in order to transform it into EFBC. It is shown, that the *TEAC* software is capable to define such big regions and perform various energy, economic and environmental analyses. Based on the obtained results, it is possible to determine the most appropriate modernisations towards the development of sustainable residential areas (*i.e.* EFBC). The smart metering techniques, PVs with batteries usage, are examined as the most comprehensive modernization. The high profitability of the above-mentioned solutions is shown. Also, a large battery applied as single energy storage for the whole BC is analysed – it is a promising solution for future sustainable design of smart-cities.

6. SUMMARY AND CONCLUSIONS

The national electricity system of Poland is mostly supplied with coal (approx. 70 % of total shares) and its' transformation is undoubtedly only a matter of time. The mentioned transformation can be performed by increasing the RES usage, but also by modernizations of out-of-date and work-out power units. Moreover, that transformation is also crucial for environmental protection – it provides a reduction of GHG emissions (especially CO_2). The environmental necessity of the Polish energetic system transformation can be motivated using a simple example. Without a drastic system modernization, an electric vehicle charged from the Polish grid will overall emit more CO_2 than a novel traditional car in 2026 (according to the already accepted EU directive). Therefore, the Polish government should consider all potentially profitable solutions to improve the national energetic system.

On the other hand, national energy consumption is defined by its consumers. From the national point of view, the main economic sectors can be considered as major consumers, in which buildings have the biggest share. In Poland, the total energy consumption by residential buildings is significantly bigger comparing with that generated by the commercial buildings. Out of the residential archetypes, single-family houses are a significant majority, as well as they are characterized by a high potential in terms of possible improvements of the so-called energy efficiency. The above-mentioned possibility is beneficial by means of financial and environmental profitability, as well as it is extremely important for the energetic stability of the national grid. Therefore, all types of energy-related analyses for the residential urban-scale areas are a basis toward changes, following the sustainable development paradigm.

Performed studies aimed to analyse the Polish residential sector and to develop an easy to use approach/tool to examine housing areas, based on the comprehensive buildings' definitions. In this PhD dissertation, three main theses were formulated:

1. advanced energy computer simulations can be used for detail predictions and analyses of energy demand profiles for a single building as well as whole residential areas;
2. the Energy Cluster concept is an appropriate and promising approach toward improvement of the energy economy as well as the development of sustainable and energy-independent urban areas;
3. it is possible to develop computational software, which is capable to perform energy-, economic- and environmental-related analyses of the Polish residential stock areas, based on buildings parameters, their mutual influences and interactions, as well as climate data.

According to the first statement, the performed studies were based on comprehensive buildings definitions and energy-related simulations, performed using the *Energy Plus* software. The validity of the *Energy Plus* software for various energy-related buildings simulations have been already proven multiple times – it is probably the best computer code for single building studies. The *Energy Plus* software allows a detail definition of the analysed building, thus obtained results are characterized with significant granularity. The *Energy Plus* software was used to define representative single-family houses of Poland and to perform several thousands of parametric simulations of these objects in the neighbourhood scenarios. The obtained outputs were furtherly used to define buildings influences and interactions, which are characteristic for urban areas. Therefore, it was possible to consider the whole housing area (built environment study) with a specificity characteristics of a singular object. All results were calculated using an hourly time step, which is a sufficient accuracy for all dynamic phenomena concerning energy consumption of single-family houses. It is concluded, that the first thesis is affirmed.

The second statement refers to the novel concept **E**nergy **C**luster (EC) and its' validity for energy- and environmental-related analyses for the urban scale zones. The main aim of this dissertation was based on multi-criteria analyses of the urban area, obtained from a numerical approach. That type of approach fits perfectly the EC definition. The performed study was based on residential areas investigations, which can be considered as **B**uilding **C**lusters (BC) or more precisely **B**uilding **E**nergy **C**lusters (BEC). All considerations following the BEC approach are in accordance with the EC concept. Some exemplary housing areas, considered as BEC, presented in the dissertation proved that usage of EC pattern is extremely valuable in terms of energy, economic and environmental profitability criteria. Additionally, it is possible to transform EC into a novel type of sustainable areas called **E**nergy **F**lexible **B**uilding **C**lusters (EFBC). Therefore, based on the presented studies it was proven, that usage of the EC concept is valid for the performed types of analyses, following the paradigm of sustainable development of urban-scale areas. The second thesis is attested.

The majority of the performed dissertation was focused on the last and third hypothesis; therefore, a computational code called *TEAC* was developed. First of all, based on the literature review presented in the theoretical background section, presently there is no software for urban-scale energy-related analyses, which allows such complexity and flexibility in buildings definition like the *Energy Plus*. Secondly, there is no tool able to perform comprehensive energy and environmental studies of the Polish residential stock. Therefore, it was determined that it is valuable to develop a simple-to-use software, which is capable to define and analyse single-family houses areas of Poland. The developed tool *TEAC* consists of several modules, used for definition and examination of housing zones, considered as BEC – the software is presented in the dissertation in detail. The biggest advantage of the *TEAC* software is the ability to predict energy demand for heating purposes, based on just few basic input parameters. The prediction process is performed by the predefined Neural Network (NN), which is characterized by results being in good agreement compared with the *Energy Plus* software outputs. Additionally, numerous calculations are performed by the *TEAC* software, in order to obtain numerous energy, economic and environmental results for the investigated BC. The advisability of the *TEAC* software application for various analyses of the residential sector of Poland was proven with some exemplary results presented in the dissertation. The developed tool is might be used by the local authorities to perform neighbourhood-, city-, commune- or even province-scale analyses. All the above-mentioned advantages of the *TEAC* software lead to a conclusion, that the third thesis is proven.

Aside from the above conclusions, which refer directly to theses stated in this dissertation, some additional useful findings were made. The results obtained using the *TEAC* software are by default presented using maps. Using that approach, it is possible to have a quick overview of the analysed area, which is helpful in terms of selecting regions, which are the most adequate to the considered issue. Therefore, zones with the highest potential of energy, economic or environmental improvement can be easily selected. Out of the *TEAC* software application, it is possible to generate a mapping of energy consumption, GHG emissions, RES outputs, as well as economic indicators summary. The concentrations of harmful GHGs can be seen effortless on the pollution maps obtained using the *TEAC* software – those outputs might be used in alerting against smog or in general low air quality analyses in the examined region. Studies performed by means of the developed software can be used for various RES analyses, such as green-energy potential in the examined region. Including all mentioned above, the *TEAC* software can be used by the Polish government or local authorities as a helpful tool for various financial support programmes (*e.g.* '*czyste powietrze*'), which the main goal is energy-, environmental- or air-quality improvement in the selected regions.

Every BC analysis performed using the *TEAC* software generates a large number of outputs, which can be presented using various figures and tables. The **L**oad **D**uration **C**urves (LDCs) are probably the most valuable ones in terms of the overall analysis of the proposed modernization scenarios. It is easy to monitor, how the examined scenarios affect the energy consumption, as well as the peak demand. This way of results presentation is extremely important in terms of the local grid perspective. Additionally, multiple financial calculations can be performed out of the *TEAC* software. It is possible to compare the modernization profitability using different calculation methods. Also, the economic indexes can be seen as time-distributed outputs. Moreover, the electricity tariff calculator is available – it allows to minimize the operation costs for the examined region. Finally, the RES potential can be checked for some predefined periods, such as 1-day or 1-week. It is even possible (but was not validated yet), to predict the potential electricity generation by RES based on the short term weather prediction, which will be applied as weather data to the *TEAC* software.

The last conclusion refers to the actual condition and energy profile of the Polish residential sector. Based on the performed analyses of the Polish archetype of single-family houses it was concluded, that the energy-related condition of the housing sector is rather poor. There are seven types of representative single-family houses of Poland, which are characterized by different construction periods, as well as building enclosure parameters. Statistically, the older the building, the poorest its energy profile (except already renovated buildings). Despite the fact, that single-family houses constructed in the past several or dozen years are considered as relatively energy-efficient ones, it is always recommended to perform some energy-related analyses exploring potential modernization profitability. Based on the performed studies it is concluded, that building modernizations are highly profitable for the Polish housing sector. The profitability is manifested by the unquestionable improvement in energy- and environmental-related aspects, as well as financial profits for some building types. Considering the necessity of modernizations, single-family houses constructed before 1985 are categorised as obligatory, these built between 1986–2002 are recommended, while these constructed after 2002 are optional but still profitable.

7. PROSPECTIVE FUTURE RESEARCHES

Prospective future researches can be categorised into two groups. The first one relates to the planned improvements of the developed *TEAC* software. Those actions are aimed at the possible dissemination of the developed computer tool. In total, seven upgrades to the *TEAC* software are formulated. The second group of the planned researches is focused on some research topics aside from the *TEAC* software.

Presently, the developed *TEAC* software should be considered as being in the alpha stage. It is stable and performs all planned actions, nevertheless, it is almost impossible to use the tool by someone alone, without the guidance of the software author. Therefore, some further works are required in order to make the software more user-friendly, as well as to consider it as a **R**eady **t**o **M**anufacture (RTM) computer code.

The first and most important improvement is to create a GUI for the *TEAC* software. The interface should allow defining the analysed neighbourhood more easily. At the beginning, the user will define the size of the analysed area and predefine its localization. Then, a definition of buildings constituting the analysed area will begin. The most appropriate approach seems to be an application of popup windows– whenever a user selects a single parcel a new window will open. In those windows, all necessary parameters will be available to input, in order to perform all further analyses in the *TEAC* software. The briefly introduced GUI will be a milestone in terms of software usability. In fact, it is planned to spread the software in the nearest future, whenever it will be a stand-alone computer application. In the beginning, it is planned to test the software by students during classes, which are focused on the UEM field, in order to receive their opinions and thoughts. Those observations will be used for further improvements of the *TEAC* software, to make it more user-friendly and intuitive. After that, the *TEAC* software will be considered as a RTM programme. Unfortunately, all efforts necessary for GUI design require a highly skilled IT specialist and software developer. Thus, it is possible to start a multi-disciplinary project/start-up focused on the final development of the *TEAC* software.

The second addition to the developed tool will be a visualization module of the defined area. At this stage, it is planned to create some kind of library with 3D building models (probably some simple sized blocks), which will be used for visualization purposes. Right now, with only seven different geometry models it seems like a quite simple task – it will be limited to load appropriate block in each parcel of the analysed zone. Nevertheless, it will become more complex, with more different building blocks, whenever the *TEAC* software is furtherly developed.

The third improvement will be focused on some upgrades of a present version of the *TEAC* software. The present stage of developed tool is introduced in detail in the dissertation. Right now, it might be considered as a comprehensive computer code for BC analyses, nevertheless, some aspects might be furtherly developed or improved. The most important enhancement relates to full flexibility in buildings' geometry definition. Right now, there are only seven sets of geometry parameters, which are representative for Polish single-family buildings stock. If the planned upgrade is implemented into the *TEAC* software, then it will be possible to perform BCs analyses for residential buildings, which vary from Polish archetype. Additionally, the present version of the software is not capable to perform valid heating predictions for variations of GHP applications (only 2 predefined scenarios are used). Therefore, further expansion of the *TEAC* database is planned. Moreover, some different operations schedules will be included.

The fourth improvement relates to the addition of various long-term predictions. Those extended estimates will include the usage of age-factor emerging in time for applied facilities and systems, influencing their reliability and efficiency. Presently, the *TEAC* software performs only the so-called one-year predictions, where the age-factor is neglected. Nevertheless, the profitability of the proposed system modernizations should be analysed including aging of those facilities (efficiency losses occurring due to their exploitation). Unfortunately, it is a very difficult task, which requires numerous analyses of systems' technical data, as well as various results published in the literature.

The fifth improvement will be focused on full LCA application for the analysed housing area using the *TEAC* software. Presently, environmental analyses are limited to GHG emissions, occurred based on energy demand (both heating and electricity). The LCA method is becoming more and more popular and it is predicted to become a standard type of analysis within the next few years. Therefore, the application of a comprehensive LCA method seems to be the unavoidable necessity required in the computer tools, which are designed for city-scale analyses. Availability of a complete LCA method as a single module in the *TEAC* software is necessary, but it is an extremely difficult task to do.

The sixth enhancement of the *TEAC* software relates to the addition of an analysis of residents' thermal comfort. In the database of results obtained by means of the *Energy Plus* software (which were used for the NN training process), the outputs of thermal comfort are already gathered, expressed using the PMV and PPD indexes at given times. Therefore, it is planned to develop a new thermal comfort module, capable to predict time distributed outputs of the PMV and PPD indexes. Additionally, it is planned, that a new module might calculate/predict thermal comfort expressed by a value of time, during which comfortable indoor conditions are obtained. Those type of analyses will be extremely valuable in terms of studying the social aspects of the sustainable development paradigm.

The seventh and last improvement proposed for the present version of the *TEAC* software is based on GIS application in order to perform case-studies of actual urban plans. Presently, those type of studies require a long pre-processing of the selected image of examined zone. The above-mentioned upgrade is considered as one of the most valuable upgrades for the programme. The usage of GIS is presently a popular approach in urban-scale modelling, nevertheless developing a valid algorithm for map scanning is an extraordinarily tough subject. Nevertheless, the *TEAC* software with GIS module would become a powerful computational software for BCs analyses.

It is also planned to perform some analyses of existing zones of single-family houses using the *TEAC* software. That type of studies will be extremely valuable in terms of further development of the code. Firstly, the validation of obtained results might be performed by comparing with real-use (consumption) data. Unfortunately, residents' consumption records are typically confidential, and their availability is limited – thus, validation of the whole BC with measured energy usage is almost impossible. Secondly, that case-studies might verify if the area definition module in the *TEAC* software is capable to reconstruct the actual size and shape of the analysed neighbourhood, with a sufficient accuracy. Finally, whenever the GIS module will be ready, it might be verified with the actual area shape.

Using a solar energy module of the *TEAC* software it is possible to estimate a potential of a PVs installation for a single-family house. Those types of buildings comprise a significant majority of the residential sector of Poland. Therefore, it might be possible to use the *TEAC* software to estimate rooftop solar PVs technical potential for the single-family houses sector of Poland. Those types of analyses would be extremely valuable in terms of the planning and development of local electric-grids. Additionally, it could help to establish local- and national-scale policies and regulations, as well as supporting financing policy.

REFERENCES

BOOKS

[1] Burton T., Sharpe D., Jenkins N., Bossanyi E., *Wind Energy Handbook, 2nd Edition*, WILEY – John Wiley and Sons, Ltd, Publication, 2011

[2] Chwieduk D., *Solar Energy in Buildings. Thermal Balance for Efficient Heating and Cooling*, Academic Press, 2014

[3] Clarke J. A., *Energy Simulation in Building Design – 2nd edition,* Butterworth-Heinemann, 2001

[4] Fanger P., *Thermal comfort: analysis and applications in environmental engineering*, Copenhagen Danish Technical Press 1970

[5] Gawin D., Kossecka E., *Komputerowa fizyka budowli: typowy rok meteorologiczny do symulacji procesów wymiany ciepła i masy w budynkach*, TUL Publishers 2002

[6] Kosny J., *PCM-Enhanced Building Components – An Application of Phase Change Materials in Building Envelopes and Internal Structures*, Springer International Publishing 2015

[7] Lefik M., *Application of artificial neural networks in mechanics and in engineering*, TUL Publishers 2005

[8] Lienhard IV J. H., Lienhard V J. H., *A heat transfer textbook – fourth edition*, Phlogiston Press, Cambridge Massachusetts, 2017

[9] Lloyd D. B., *The Smart Guide to Geothermal: How to Harvest Earth's Free Energy for Heating and Cooling*, PixyJack Press, 2011

[10] Manwell J. F., Mcgowan J.G., Rogers A. L., *Wind Energy Explained. Theory, Design and Application – Second Edition*, WILEY – John Wiley and Sons, Ltd, Publication, 2011

[11] Tiwari G.N., Tiwari A., Shyam, *Handbook of Solar Energy. Theory, Analysis and Applications*, Springer Ltd, 2016

[12] Villalba B., *Energy Sobriety Policies: Territorialisation and Institutionalisation at a Regional Level*, European Consortium for Political Research General Conference, Bordeaux, France 2013

[13] Wyrwał J., *Termodynamiczne podstawy fizyki budowli*, Oficyna Wydaw. Politechniki Opolskiej, Opole, 2004

ARTICLES

[14] Abid F., Hamami L., *A survey of neural network based automated systems for human chromosome classification*, Artificial Intelligence Review 2018, vol. 49, 41-56

[15] Abiodun I. O., Jantan A., Omolara E. A., Dada V. K., Mohamed A. N., Arshad H., *State-of-the-art in artificial neural network applications: A survey*, Heliyon 2018, vol. 4 (11)

[16] Alam M., Singh H., Limbachiya M. C., *Vacuum Insulation Panels (VIPs) for building construction industry – A review of the contemporary development and future directions*, Applied Energy 2011, vol. 88, 3592-3602

[17] Albatici R., Passerini F., *Bioclimatic design of buildings considering heating requirements in Italian climatic conditions. A simplified approach*, Building and Environment 2011, vol. 46, 1624-1631

[18] AlFuhaid S. A., El-Sayed A. M., Mahmoud S. M., *Cascaded artifilcal neural networks for short-term load forecasting*, IEEE Transactions on Power Systems 1997, vol. 12 (4), 1524-1529

[19] Al-Homound M. S., *Performance characteristics and practical applications of common building thermal insulation materials*, Building and Environment 2005, vol. 40, 353-366

[20] Al-Khatatbeh B. J., Ma'bdeh S. N., *Improving visual comfort and energy efficiency in existing classrooms using passive daylighting techniques*, Energy Procedia 2017, vol. 136, 102-108

[21] Amstalden R. W., Kostm M. Nathani C., Imboden D. M., *Economic potential of energy-efficient retrofitting in the Swiss residential building sector. The effects of policy instruments and energy price expectations*, Energy Policy 2007, vol. 35 (3), 1819-1829

[22] Anderson T. N., Duke M., Morrison G. L., Carson J. K., *Performance of a building integrated photovoltaic/thermal (BIPVT) solar collector*, Solar Energy 2009, vol. 83, 445-455

[23] Annunziata E., Frey M., Rizzi F., *Towards nearly zero-energy buildings: The state-of-art of national regulations in Europe*, Energy 2013, vol. 57, 125-133

[24] Antoniadou P., Papadopoulos A. M., *Occupants' thermal comfort: State of the art and the prospects of personalized assessment in office buildings*, Energy and Buildings 2017, vol. 153, 136-149

[25] Arici M., Karabay H., Kan M., *Flow and heat transfer in double, triple and quadruple pane windows*, Energy and Buildings 2015, vol. 86, 394-402

[26] Ascione F., De Masi R. F., Rossi F., Fistola R., Sasso M., Vanoli G. P., *Analysis and diagnosis of the energy performance of buildings and districts: Methodology, validation and development of Urban Energy Maps*, Cities 2013, vol. 35, 270-283

[27] Asiedu Y., Gu P., *Product life cycle analysis: State of the art review*, International Journal of Production Research 1998, vol. 36 (4), 883-908

[28] Aydinalp M., Ugursal VI, Fung A., *Modeling of the appliance, lighting, and space cooling energy consumptions in the residential sector using neural networks*, Applied Energy 2002, vol. 72 (2), 87-110

[29] Aydinalp M., Ugursal VI, Fung A., *Modeling of the space and domestic hot-water heating energy-consumption in the residential sector using neural networks*, Applied Energy 2004, vol. 79 (2), 159-178

[30] Ayhan D., Saglam S., *A technical review of building-mounted wind power systems and a sample simulation model*, Renewable and Sustainable Energy Reviews 2012, vol. 16, 1040-1049

[31] Baetens R., Jelle B. P., Gustavsen A., *Aerogel insulation for building applications: A state-of-the-art review*, Energy and Buildings 2011, vol. 43, 761-769

[32] Baetens R., Jelle B. P., Gustavsen A., *Phase change materials for building applications: A state-of-the-are review*, Energy and Buildings 2010, vol. 42 (9), 1361-1368

[33] Baetens R., Jelle B. P., Gutavsen A., *Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review*, Solar Energy Materials & Solar Cells 2010, vol. 94 (2), 87-105

[34] Baetens R., Jelle B. P., Thue J. V., Tenpierik M. J., Grynning S., Uvslokk S., Gustavsen A., *Vacuum insulation panels for building applications: A review and beyond*, Energy and Buildings 2010, vol. 42, 147-172

[35] Bahar Y. N., Pere C., Landrieu J., Nicolle C., *A Thermal Simulation Tool for Building and Its Interoperability through the Building Information Modeling (BIM) Platform*, Buildings 2013, vol. 3 (2), 380-398

[36] Bayer P., Saner D., Bolay S., Rybach L., Blum P., *Greenhouse gas emission savings of ground source heat pump systems in Europe: A review*, Renewable and Sustainable Energy Reviews 2012, vol. 16, 1256-1267

[37] Belussi L., Barozzi B., Bellazzi A., Danza L., Devitofrancesco A., Fanciulli C., Ghellere M., Guazzi G., Meroni I., Salamone F., Scamoni F., Scrosati C., *A review of performance of zero energy buildings and energy efficiency solutions*, Journal of Building Engineering 2019, vol. 25

[38] Bentzen J., Engsted T., *A revival of the autoregressive distributed lag model in estimating energy demand relationships*, Energy 2001, vol. 26 (1), 45-55

[39] Bichiou Y., Krarti M., *Optimization of envelope and HVAC systems selection for residential buildings*, Energy and Buildings 2011, vol. 43, 3373-3382

[40] Booth A. T., Choudhary R., Spiegelhalter D. J., *Handling uncertainty in housing stock models*, Building and Environment 2012, vol. 48, 35-47

[41] Cabeza F. L., Rincon L., Vilarino V., Perez G., Castell A., *Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review*, Renewable and Sustainable Energy Reviews 2014, vol. 29, 394-416

[42] Canyurt O. E., Ozturk K. H., Hepbasli A., Utlu Z., *Estimating the Turkish residential–commercial energy output based on genetic algorithm (GA) approaches*, Energy Policy 2005, vol. 33 (8), 1011–1019

[43] Cao X., Dai X., Liu J., *Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade*, Energy and Buildings 2016, vol. 128, 198-213

[44] Caputo P., Costa G., Ferrari S., *A supporting method for defining energy strategies in the building sector at urban scale*, Energy Policy 2013, vol. 55, 261-270

[45] Carlo J., Ghisi E., Lamberts R., *The use of computer simulation to establish energy efficiency parameters for a building code of a city in Brazil*, IBPSA - eighth international conference, Eindhoven, Netherlands, 2003

[46] Casini A., *Active dynamic windows for buildings: A review*, Renewable Energy 2018, vol. 119, 923-934

[47] Catalina T., Virgone J., Iordache V., *Study on the impact of the building form on the energy consumption*, Proceeding of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November

[48] Caves D. W., Herriges J. A., Train K. E., Windle R., *A Bayesian approach to combining conditional demand and engineering models of electricity usage*, The Review of Economics and Statistics 1987, vol. 69 (3), 438-448

[49] Chan A. L. S., *Developing a modified typical meteorological year weather file for Hong Kong taking into account the urban heat island effect*, Building and Environment 2011, vol. 46 (12), 2434-2441

[50] Chau K. C., Leung M. T., Ng Y. W., *A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings*, Applied Energy 2015, vol. 143, 395-413

[51] Chel A., Kaushik G., *Renewable energy technologies for sustainable development of energy efficient building*, Alexandria Engineering Journal 2018, vol. 57, 655-669

[52] Chen Y., Hong T., Piette M. A., *Automatic generation and simulation of urban building energy models based on city dataset for city-scale building retrofit analysis*, Applied Energy 2017, vol. 205, 323-335

[53] Cheng V., Steemers K., *Modelling domestic energy consumption at district scale: a tool to support national and local energy policies*, Environmental Modelling & Software 2011, vol. 26 (10), 1186-1198

[54] Cheng-wen Y., Jian J. Y., *Application of ANN for the prediction of building energy consumption at different climate zones with HDD and CDD*, 2010 2nd International Conference on Future Computer and Communication 2010, vol. 3, 286-289

[55] Chow T-t., Li C., Lin Z., *Innovative solar windows for cooling-demand climate*, Solar Energy Materials & Solar Cells 2010, vol. 94, 212-220

[56] Claridge E. D., *A Perspective on Methods for Analysis of Measured Energy Data from Commercial Buildings*, Journal of Solar Engineering 1998, vol. 120 (3), 150-155

[57] Corrado V., Ballarini I., *Refurbishment trends of the residential building stock: Analysis of a regional pilot case in Italy*, Energy and Buildings 2016, vol. 132, 91-106

[58] Crawley D. B., Hand J. W., Kummert M., Griffith B.T., *Contrasting the capabilities of building energy performance simulation programs*, Building and Environment 2005, vol. 43 (4), 661-673

[59] Crawley D. B., Lawrie L. K., Winkelmann F.C., Buhl W. F., Huang Y. J., Pedersen C. O., Stand R. K., Liesen R. J., Fisher D. E., Witte M. J., Glazer J., *EnergyPlus: creating a new-generation building energy simulation program,* Energy and Buildings 2001, vol. 33, 319-331

[60] Csoknyai T., Hrabovszky-Horvath S., Georgiev Z., Jovanovic-Popovic M., Stankovic B., Villatoro O., Szendro G., *Building stock characteristics and energy performance of residential buildings in Eastern-European countries*, Energy and Buildings 2016, vol. 132, 39-52

[61] Cuce E., Cuce P. M., *Vacuum glazing for highly insulating windows: Recent developments and future prospects*, Renewable and Sustainable Energy Reviews 2016, vol. 54, 1345-1357

[62] Cuce E., Cuce P. M., Wood C. J., Riffat S. B., *Optimizing insulation thickness and analysing environmental impacts of aerogel-based thermal superinsulation in buildings*, Energy and Buildings 2014, vol. 77, 28-39

[63] Cuce E., Cuce P. M., Wood C. J., Riffat S. B., *Toward aerogel based thermal superinsulation in buildings: A comprehensive review*, Renewable and Sustainable Energy Reviews 2014, vol. 34, 273-299

[64] Cuce E., Riffat S. B., *A state-of-the-art review on innovative glazing technologies*, Renewable and Sustainable Energy Reviews 2015, vol. 41, 695-714

[65] Dascalaki E. G., Balaras C. A., Kontoyiannidis S., Droutsa K. G., *Modeling energy refurbishment scenarios for the Hellenic residential building stock towards the 2020 & 2030 targets*, Energy and Buildings 2016, vol. 132, 74-90

[66] Demirbas M. F., *Thermal Energy Storage and Phase Change Materials: An Overview*, Energy Sources, Part B: Economics, Planning and Policy 2006, vol. 1 (1), 85-95

[67] Depecker P., Menezo C., Virgone J., Lepers S., *Design of buildings shape and energetic consumption*, Building and Environment 2001, vol. 36, 627-635

[68] Diefenbach N., Loga T., Stein B., *Reaching the climate protection targets for the heat supply of the German residential building stock: How and how fast?,* Energy and Buildings 2016, vol. 132, 53-73

[69] Ding Y., Fu Q., Tian Z., Li M., Zhu N., *Influence of indoor design air parameters on energy consumption of heating and air conditioning*, Energy and Buildings 2013, vol. 56, 78-84

[70] Dong B., Prakash V., Feng F., O'Neill Z., *A review of smart building sensing system for better indoor environment control*, Energy and Buildings 2019, vol. 199, 29-46

[71] Eames P. C., *Vacuum glazing: Current performance and future prospects*, Vacuum 2008, vol. 82 (7), 717-722

[72] Esen M., Yuksel T., *Experimental evaluation of using various renewable energy sources for heating a greenhouse*, Energy and Buildings 2013, vol. 65, 340-351

[73] Farahbakhsh H., Ugursal VI, Fung A., *A residential end-use energy consumption model for Canada*, International Journal of Energy Research 1998, vol. 22 (13), 1133-1143

[74] Farid M. M., Khudhair A. M., Razack S. A. K., Al-Hallaj S., *A review on phase change energy storage: materials and applications*, Energy Conversion & Management 2004, vol. 45, 1597-1615

[75] Ferreira J., Pinheiro M., *In search of better energy performance in the Portuguese buildings—The case of the Portuguese regulation*, Energy Policy 2011, vol. 39, 7666-7683

[76] Foucquier A., Robert S., Suard F., Stephan L., Jay A., *State of the art in building modeling and energy performances predicitons: A review,* Renewable and Sustainable Energy Reviews 2013, vol. 23, 272-288

[77] Frid S. E., Lisitskaya N. V., *State-of-the-Art Solar Collectors: Typical Parameters and Trends*, Applied Solar Energy 2018, vol. 54, 279-286

[78] Firth S. K., Lomas K. J., Wright A. J., *Targeting household energy efficiency measures using sensitivity analysis*, Building Research and Information 2010, vol. 38 (1), 25-41

[79] Frontczak M., Wargocki P., *Literature survey on how different factors influence human comfort in indoor environments*, Building and Environment 2011, vol. 46, 922-937

[80] Gagliano A., Patania F., Nocera F., Signorello C., *Assessment of the dynamic thermal performance of massive buildings*, Energy and Buildings 2014, vol. 72, 361-370

[81] Gagon P., Margolis R., Melius J., Phillips C., Elmore R., *Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment*, National Renewable Energy Laboratory 2016

[82] Galvao G. D. A., Nadae J., Clemente D. H., Chinen G., Carvalho M. M., *Circular Economy: Overview of Barriers*, Science Direct Procedia CIRP 2018, vol. 73, 79-85

[83] Gangopadhyay U., Jana S., Das S., *State of Art of Solar Photovoltaic Technology*, International Conference on Solar Energy Photovoltaics 2013

[84] Gao T., Ihara T., Grynning S., Jelle B. P., Lien A. G., *Perspective of aerogel glazings in energy efficient buildings*, Building and Environment 2016, vol. 95, 405-413

[85] Gao T., Jelle B. P., Gustavsen A., *Building integration of aerogel glazings*, Procedia Engineering 2016, vol. 145, 723-728

[86] Gavin H. P., *The Lavenberg-Marquardt method for nonlinear least squares curve-fitting problems*, Computer Science 2013

[87] Geissdoerfer M., Savaget P., Bocken N. M. P., Hultink E. J., *The Circular Economy – A new sustainability paradigm?*, Journal of Cleaner Production 2017, vol. 143, 757-768

[88] Gelazanskas L., Gamage K. A. A., *Demand side management in smart grid: A review and proposals for future direction*, Sustainable Cities and Society 2014, vol. 11, 22-30

[89] Geletka V., Sedlakova A., *Shape of building and energy consumption*, Technical Transactions – Civil Engineering 2011, vol. 8, 46-53

[90] Ghisellini P., Cialani C., Ulgiati S., *A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems*, Journal of Cleaner Production 2016, vol. 114, 11-32

[91] Giarma C., Tsikaloudaki K., Aravantinos D., *Daylighting and Visual Comfort in Buildings' Environmental Performance Assessment Tools: a Critical Review*, Procedia Environmental Sciences 2017, vol. 38, 522-529

[92] Goia F, Perino M., Sera V., *Experimental analysis of the energy performance of a full-scale PCM glazing prototype*, Solar Energy 2014, vol. 100, 217-233

[93] Griffith B., Crawley D., *Methodology for analyzing the technical potential for energy performance in the U.S. commercial buildings sector with detailed energy modeling*, IBPSA-USA, SimBuild conference, Cambridge, Massachusetts, 2006

[94] Grynning S., Gustavsen A., Time B., Jelle B. P., *Windows in the buildings of tomorrow: Energy losers or energy gainers?*, Energy and Buildings 2013, vol. 61, 185-192

[95] Guen M., Mosca L., Perera A. T. D., Coccolo S., Mohajer N., Scartezzini J-L., *Improving the energy sustainability of a Swiss village through building renovation and renewable energy integration*, Energy and Building 2018, vol. 158, 906-923

[96] Gustafsson S-I., *Optimal fenestration retrofits by use of MILP programming technique*, Energy and Buildings 2001, vol. 33, 843-851

[97] Gustavsen A., Jelle B. P., Arasteh D. K., Kohler C., *State-of-the-Art Highly Insulating Windows Frames – Research and Market Review*, INTEF Building and Infrastructure 2007

[98] Hamedani A. Z., Huber F., *A comparative study of DGNB, LEED and BREEAM certificate systems in urban sustainability*, WIT Transactions on Ecology and The Environment 2012, vol. 155, 121-132

[99] Hasnain S. M., *Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques*, Energy Conversion and Management 1998, vol. 39 (11), 1127-1138

[100] Hayter S. J., Kandt A., *Renewable Energy Applications for Existing Buildings*, National Renewable Energy Laboratory (NREL), 2011

[101] Heiple S., Sailor D. J., *Using building energy simulation and geospatial modeling techniques to determine high resolution building sector energy consumption profiles*, Energy and Buildings 2008, vol. 40 1426-1436

[102] Henninger R. H., Witte M. J., Crawley D. B., *Analytical and comparative testing of EnergyPlus using IEA HVAC BESTEST E100-E200 test suite*, Energy and Buildings 2004, vol. 36, 855-863

[103] Hernandez L., Baladron C., Aguiar M. J., Carro B., Sanchez-Esguevillas J. A., Lloret J., *Short-Term Load Forecasting for Microgrids Based on Artifical Neural Network*, Energies 2013, vol. 6, 1385-1408

[104] Hirst E., Lin W., Cope J., *A residential energy use model sensitive to demographic, economic and technological factors*, Quarterly Review of Economics and Finance 1977, vol. 17 (2), 7-22

[105] Hirst E., *A model of residential energy use*, Simulation 1978, vol. 30 (3), 69-74

[106] Hirst E., Goeltz R., White D., *Determination of household energy using 'fingerprints' from energy billing data*, Energy Research 1986, vol. 10 (4), 393-405

[107] Hongwei T., Yong L., Yibo C., *Renewable Energy Development for Buildings*, Energy Procedia 2016, vol. 103, 88-93

[108] Hoppmann J., Volland J., Schmidt T. S., Hoffmann V. H., *The economic visibility of battery storage for residential solar photovoltaic systems – A review and a simulation model*, Renewable and Sustainable Energy Reviews 2014, vol. 39, 1101-1118

[109] Hottel H., Woertz B., *Performance of flat-plate solar-heat collectors*, Transactions of American Society of Mechanical Engineers 1942, vol. 64 (91), 91-104

[110] Igliński B., Iglińska A., Koziński G., Skrzatek M., Buczkowski R., *Wind energy in Poland – History, current state, surveys, Renewable Energy Sources Act, SWOT analysis*, Renewable and Sustainable Energy Reviews 2016, vol. 64, 19-33

[111] Ignatius M., Wong N. H., Jusuf S. K., *Urban microclimate analysis with consideration of local ambient temperature, external heat gain, urban ventilation, and outdoor thermal comfort in the tropics*, Sustainable Cities and Society 2015, vol. 19, 121-135

[112] Ishugah T. F., Li, Y., Wang R. Z., Kiplagat J. K., *Advances in wind energy resource exploitation in urban environment: A review*, Renewable and Sustainable Energy Reviews 2014, vol. 37, 613-626

[113] Islam H., Jollands M., Setunge S., *Life cycle assessment and life cycle implication of residential buildings – A review*, Renewable and Sustainable Energy Reviews 2015, vol. 42, 129-140

[114] Jaccard M., Baille A., *CO2 emission reduction costs in the residential sector: behavioral parameters in a bottom-up simulation model*, Energy 1996, vol. 17 (4), 107-135

[115] Jaggs M., Palmer J., *Energy performance indoor environmental quality retrofit – a European diagnosis and decision making method for building refurbishment*, Energy and Buildings 2000, vol. 31, 97-101

[116] Jelle B. P., *Traditional, state-of-the-art future thermal building insulation materials and solutions – Properties, requirements and possibilities*, Energy and Buildings 2011, vol. 43, 2549-2563

[117] Jelle B. P., Breivik C., *State-of-the-art building integrated photovoltaics*, Energy Procedia 2012, vol. 20, 68-77

[118] Jelle B. P., Breivik C., *The path to the building integrated photovoltaics of tomorrow*, Energy Procedia 2012, vol. 20, 78-87

[119] Jelle B. P., Breivik C., Rokenes H. D., *Building integrated photovoltaic products: A state-of-the-art review and future research opportunities*, Solar Energy Materials & Solar Cells 2012, vol. 100, 69-96

[120] Jelle B. P., Gustavsen A., Baetens R., *The path to the high performance thermal building insulation materials and solutions of tomorrow*, Journal of Building Physics 2010, vol. 34 (2), 99-123

[121] Jelle B. P., Hynd A., Gutavsen A., Arasteh D., Goudey H., Hart R., *Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities*, Solar Energy Materials & Solar Cells 2012, vol. 96, 1-28

[122] Jelle B. P., Kalanes S. E., Gao T., *Low-emissivity materials for building applications: A state-of-the-art review and future research perspectives*, Energy and Buildings 2015, vol. 96, 329-356

[123] Jensen S. O., Marszal-Pomianowska A., Lollini R., Pasut W., Knotzer A., Engelmann P., Reynders G., *IEA EBC Annex 67 Energy Flexible Buildings*, Energy and Buildings 2017, vol. 155, 25-34

[124] Jones J. K., Harp S. L., *Residential energy analysis using modified degree day procedures*, American Society of Agricultural Engineers, 1980

[125] Kadian R., Dahiya R. P., Garg H. P., *Energy-related emissions and mitigation opportunities from the household sector in Delhi*, Energy Policy 2007, vol. 35 (12), 6195-6211

[126] Kalnaes S. E., Jelle B. P., *Phase change materials and products for buildings applications: A state-of-the-art review and future research opportunities*, Energy and Buildings 2015, vol. 94,. 150-176

[127] Kalnaes S. E., Jelle B. P., *Vacuum insulation panel products: A state-of-the-art review and future research pathways*, Applied Energy 2014, vol. 116, 355-375

[128] Kalogirou S. A., *Artificial neural network in energy applications in buildings*, International Journal of Low-Carbon Technologies 2006, vol. 1 (3), 201-216

[129] Kalogirou S. A., *Solar thermal collectors and applications*, Progress in Energy and Combustion Science 2004, vol. 30, 231-295

[130] Kalz D. E., Pfafferott J., Herkel S., *Building signatures: A holistic approach to the evaluation of heating and cooling concepts*, Building and Environment 2010, vol. 45, 632-646

[131] Kavgic M., Mavrogianni A., Mumovic D., Summerfield A., Stevanovic Z., Djurovic-Petrovic M., *A review of bottom-up building stock models for energy consumption in the residential sector*, Building and Environment 2010, vol. 45, 1683-1697

[132] Khan R. A., Mahmood A., Safdar A., Khan A. Z., Khan A. N., *Load forecasting dynamic pricing and DSM in smart grid: A review*, Renewable and Sustainable Energy Reviews 2016, vol. 54, 1311-132

[133] Khudhair A. M., Farid M. M., *A review on energy conservation in building applications with thermal storage by latent heat using phase change materials*, Energy Conversion and Management 2004, vol. 45 (2), 263-275

[134] Kim E-J., Plessis G., Hubert J-L., Roux J-J., *Urban energy simulation: Simplification and reduction of building envelope models*, Energy and Buildings 2014, vol. 84, 193-202

[135] Kisilewicz T., *On the Role of External Walls in the Reduction of Energy Demand and the Mitigation of Human Thermal Discomfort*, Sustainability 2019, vol 11 (4), 1061

[136] Kisilewicz T., *Performance of building materials and whole enclosures in non-stationary thermal conditions*, Procedia Engineering 2015, vol. 108, 445-452

[137] Kisilewicz T., Fedorczak-Cisak M., Barkanyi T., Active thermal insulation as an element limiting heat loss through external walls, Energy and Buildings 2019, vol. 205, 109541

[138] Kohler N., Hassler U., *The building stock as a research object*, Building Research & Information 2002, vol. 40 (4), 226-236

[139] Kolokotroni M., Giannitsaris I., *Urban heat island intensity in London: An investigation of the impact of physical characteristics on changes in outdoor air temperature during summer*, Solar Energy 2008, vol. 82 (11), 986-998

[140] Kolokotroni M., Giannitsaris I., Watkins R., *The effect of the London urban heat island on building summer cooling demand and night ventilation strategies*, Solar Energy 2006, vol. 80 (4), 383-392

[141] Kolokotsa D., Diakaki C., Grigoroudis E., Stavrakakis G., Kalaitzakis K., *Decision support methodologies on energy efficiency and management in buildings*, Advances in Building Energy Research 2009, vol. 3 (1), 121-146

[142] Kondziella H., Bruckner T., *Flexibility requirements of renewable energy based electricity systems – A review of research results and methodologies*, Renewable and Sustainable Energy Reviews 2016, vol. 53, 10-22

[143] Kontokosta C. E., Tull C., *A data-driven predictive model of city-scale energy use in buildings*, Applied Energy 2017, vol. 197, 303-17

[144] Kosny J., Fallahi A., Shukla N., Kossecka E., Ahbari R., *Thermal load mitigation and passive cooling in residential attics containing PCM-enhanced insulations*, Solar Energy 2014, vol. 108, 164-177

[145] Kralj A., Drev M., Znidarsic M., Cerne B., Hafner J., Jelle B. P.*, Investigations of 6-pane glazing: Properties and possibilities*, Energy and Buildings 2019, vol. 190, 61-68

[146] Krupa K., Nieradko L., Haraziński A., *Prospect for energy storage in the world and in Poland in the 2030 horizon*, Energy Policy Journal 2018, vol. 21 (2), 19-34

[147] Kumar R., Raahemifar K., Fung A. S., *A critical review of vertical axis wind turbines for urban applications*, Renewable and Sustainable Energy Reviews 2018 vol. 89, 281-291

[148] Kuznik F., Virgone J., Roux J-J., *Energetic efficiency of room wall containing PCM wallboard: A full-scale experimental investigation*, Energy and Buildings 2008, vol. 40, 148-156

[149] LaFrance G., Perron D., *Evolution of residential electricity demand by end-use in Quebec 1979-1989: a conditional demand analysis*, Energy Studies Review 1994, vol. 6 (2), 164-173

[150] Lampropoulos I., Kling W. L., Ribeiro P. F., *History of demand side management and classification of demand response control schemes*, IEEE Power & Energy Society General Meeting, 2013

[151] Lara A. R., Naboni E., Pernigotto G., Cappelletti F., Zhang Yi, Barzon F., Gasparella A., Romagnoni P., *Optimization Tools for Building Energy Model Calibration*, Energy Procedia 2017, vol. 111, 1060-1069

[152] Larsen B. M., Nesbakken R., *Household electricity end-use consumption: results from econometric and engineering models*, Energy Economics 2004, vol. 26 (2), 179-200

[153] Launhardt T., Thoma H., *Investigation on organic pollutants from a domestic heating system using various solid biofuels*, Chemosphere 2000, vol. 40 (9-11), 1149-1157

[154] Leccese F., Salvadori G., Asdrubali F. Gori P., *Passive thermal behaviour of buildings: Performance of external multi-layered walls and influence of internal walls*, Applied Energy 2018, vol. 225, 1078-1089

[155] Leising E., Quist J., Bocken N., *Circular Economy in the building sector: Three cases and a collaboration tool*, Journal of Cleaner Production 2018, vol. 176, 976-989

[156] Levenberg K., *A method for the solution of certain non-linear problem in least squares*, Quarterly of Applied Mathematics 1944, vol. 2, 164-168

[157] Liang Y., Wu H., Huang G., Yang J., Wang H., *Thermal performance and service life of vacuum insulation panels with aerogel composite cores*, Energy and Buildings 2017, vol. 154 (1), 606-617

[158] Liu B. Y., Jordan R. C., *The long term average performance of flat-plate solar energy collectors*, Solar Energy 1963, vol. 7 (2), 53-74

[159] Liu L., Rohdin P., Moshfegh B., *Investigating cost-optimal refurbishment strategies for the medieval district of Visby in Sweden*, Energy in Buildings 2018, vol. 158, 750-760

[160] Lu T., Lu X., Viljanen M., *A new model for modeling energy performance in buildings*, Energy Procedia 2015, vol. 75, 1825-1831

[161] Lucia U., Simonetti M., Chiesa G., Grisolia G., *Ground-source pump system for heating and cooling: Review and thermodynamic approach*, Renewable and Sustainable Energy Reviews 2017, vol. 70, 867-874

[162] Lomas K. J., Eppel H., *Sensitivity analysis techniques for building thermal simulation programs,* Energy and Buildings 1992, vol. 19, 21-44

[163] Lopez C. D., Carpio M., Martin-Morales M., Zamorano M., *A comparative analysis of sustainable building assessment methods*, Sustainable Cities and Society 2019, vol. 49

[164] Ma J., Cheng J. C. P., *Estimation of the building energy use intensity in the urban scale by integrating GIS and big data technology*, Applied Energy 2016, vol. 183, 182-92

[165] Ma R., Ren B., Zhao D., Chen J., Lu Y., *Modelling urban energy dynamics under clustered urban heat Island effect with local-weather extended distributed adjacency blocks*, Sustainable Cities and Society 2020, vol. 56

[166] Ma Z., Cooper P., Daly D., Ledo L., *Existing building retrofits: Methodology and state-of-the-art*, Energy and Buildings 2012, vol. 55, 889-902

[167] Macdonald I., Clarke J., *Applying uncertainty considerations to energy conservation equations*, Energy and Buildings 2007, vol. 39, 1019-1026

[168] Manic M., Wijayasekara D., Amarasinghe K., Rodriguez-Andina J. J., *Building Energy Management Systems: The Age of Intelligent and Adaptive Buildings*, IEEE Industrial Electronics Magazine 2016

[169] Marks W., *Multicriteria Optimisation of Shape of Energy-Saving Buildings*, Building and Environment 1997, vol. 32 (4), 331-339

[170] Marszal A. J., Heiselberg P., Bourrelle J. S., Musall E., Voss K., Sartori I., Napolitano A., *Zero Energy Building – A review of definitions and calculation methodologies*, Energy and Buildings 2011, vol. 43 (4), 971-979

[171] Marino C., Nucara A., Panzera M. F., Pietrafesa M., *Towards the nearly zero and the plus energy buildings: Primary energy balances and economic evaluations*, Thermal Science and Engineering Progress 2019, vol. 13

[172] Marquardt D., *An Algorithm for Least-Squares Estimation of Nonlinear Parameters*, Journal of the Society for Industrial and Applied Mathematics 1963, vol. 11 (2), 431-441

[173] Maroufmashat A., Elkamel A., Fowler M., Sattari S., Roshandel R., Hajimiragha A., Walker S., Entchev E., *Modeling and optimization of a network of energy hubs to improve economic and emission considerations*, Energy 2015, vol. 93 (2), 2546-2558

[174] Mastrucci A., Baume O., Stazi F., Leopold U., *Estimating energy savings for the residential building stock of an entire city: a GIS-based statistical downscaling approach applied to Rotterdam*, Energy and Buildings 2014, vol. 14, 358-367

[175] Mata E., Kalagasidis A.S., Johnsson F., *A modelling strategy for energy, carbon and cost assessments of building stocks*, Energy and Buildings 2013, vol. 56, 100-108

[176] Mathiesen B. V., Lund H., Connolly D., Wenzel H., Ostergaard P. A., Moller B., Nielsen S., Ridjan I., Karnoe P., Sperling K., Hvelplund F. K., *Smart Energy Systems for coherent 100% renewable energy and transport solutions*, Applied Energy 2015, vol. 145 (1), 139-154

[177] Mauro G. M., Hamdy M., Vanoli G. P., Bianco N., Hensen J. L. M., *A new methodology for investigating the cost-optimality of energy retrofitting a building category*, Energy and Buildings 2015, vol. 107, 456-478

[178] Mazzarella L., *Energy retrofit of historic and existing buildings. The legislative and regulatory point of view*, Energy and Building 2015, vol. 95, 23-31

[179] McKeen P., Fung A. S., *The effect of building aspect ratio on energy efficiency: a case study for multi-unit residential buildings in Canada*, Buildings 2014, vol. 4, 336-354

[180] McKenna R., Merkel E., Fehrenbach D., Mehne S., Fichtner W., *Energy efficiency in the German residential sector: a bottom-up building-stock-model-based analysis in the context of energy-political targets*, Building and Environment 2013, vol. 62, 77-88

[181] Memon S. A., *Phase change materials integrated in building walls: A state of the art review*, Renewable and Sustainable Energy Reviews 2014, vol. 31, 870-906

[182] Meyabadi F. A., Deihimi H. M., *A review of demand-side management: Reconsidering theoretical framework*, Renewable and Sustainable Energy Reviews 2017, vol. 80, 367-379

[183] Mickaityte A., Zavadskas E. K., Kaklauskas A., Tupenaite L., *The concept model of sustainable buildings refurbishment*, International Journal of Strategic Property Management 2008, vol. 12 (1), 53-68

[184] Midtdal K., Jelle B. P., *Self-cleaning glazing products: A state-of-the-art review and future research pathways*, Solar Energy Materials & Solar Cells 2013, vol. 109, 126-141

[185] Mihalakakou G., Santamouris M., Tsangrassoulis A., *On the energy consumption in residential buildings*, Energy and Buildings 2002, vol. 34 (7), 727-36

[186] Mohajer N., Perera A. T. D., Coccolo S., Mosca L., Guen M., Scartezzini J-L., *Integrating urban from and distributed energysystems: Assessment of sustainable development scenario for a Swiss village to 2050*, Renewable Energy 2019, vol. 143, 810-826

[187] Morrissey J., Horne R.E., *Life cycle cost implications of energy efficiency measures in new residential buildings*, Energy and Buildings 2011, vol. 43, 915-924

[188] Muratori M., Roberts M. C., Sioshansi R., Marano V., Rizzoni G., *A highly resolved modeling technique to simulate residential power demand*, Applied Energy 2013, vol. 107, 465-473

[189] Narowski P., *Energy clusters as an example of energy communities in Poland – policy and results*, The Polish National Energy Conservation Agency, Riga, 21 June 2018

[190] Narowski P., Heim D., *Climate data for modelling of hydro-thermal processes in building elements*, Building Physics in Theory and Practice 2008, vol. 3, 85-91

[191] Natarajan S., Padget J., Elliott L., *Modelling UK domestic energy and carbon emissions: an agent-based approach*, Energy and Buildings 2011, vol. 43, 2602-2612

[192] Navai M., Veitch J. A., *Acoustic Satisfaction in Open-Plan Offices: Review and Recommendations*, National Research Council Canada, 2003

[193] Nemry F., Uihlein A., Colodel C. M., Wetzel C., Braune A., Wittstock B., Hasan I., Kreissig J., Gallon N., Niemier S., Frech Y., *Options to reduce the environmental impacts of residential buildings in the European Union – Potential and costs*, Energy and Buildings 2010, vol. 42, 976-984

[194] Neto H. A., Fiorelli S. A. F., *Comparison between detailed model simulation and artificial neural network for forecasting building energy consumption*, Energy and Building 2008, vol. 40, 2169-2176

[195] Ng N., Collins R. E., So L., *Characterization of the thermal insulation properties of vacuum glazing*, Material Science and Engineering: B 2007, vol. 138 (2), 128-134

[196] Nilsson L. J., Pisarek M., Buriak J., Oniszk-Popławska A., Bućko P., Ericsson K., Jaworski L., *Energy policy and the role of bioenergy in Poland*, Energy Policy 2006, vol. 34, 2263-2278

[197] Nowak H., Nowak Ł., Śliwińska E., *The impact of different solar passive systems on energy savings in public buildings and occupants' thermal and visual comfort*, Journal of Building Physics 2015, vol. 40 (2), 1-23

[198] .Nowak H., Nowak Ł., Śliwińska E., Staniec M., *Effect of horizontal overhangs and glazing with spectral radiative properties on annual thermal balance of the building and thermal comfort*, Proceedings of the 2nd Central European Symposium on Building Physics, Vienna 2013

[199] Nowak H., Włodarczyk D., Nowak Ł., Śliwińska E., Staniec-Birus M., *Analyse of the active and passive solar systems in the low-energy public buildings in Poland*, Technical Transactions. Civil Engineering 2010, vol. 107 (4), 143-152

[200] Oke T. R., *City size and the urban heat island*, Atmospheric Environment 1973, vol. 7 (8), 769-779

[201] Olesen B. W., Kazanci O. B., *State of the Art of HVAC Technology in Europe and America*, Proceedings of the World Engineering Conference and Convention 2015 (WECC2015)

[202] O'Neal D. L., Hirst E., *An energy use model of the residential sector*, IEEE Transactions on Systems, Man and Cybernetics 1980, vol. 10 (11), 749-755

[203] Ourghi R., Al-Anzi A., Krarti M., *A simplified analysis method to predict the impact of shape on annual energy use for office buildings*, Energy Conversion & Management 2007, vol. 48, 300-305

[204] Ozturk K. H., Canyurt O. E., Hepbasli A., Utlu Z., *Residential–commercial energy input estimation based on genetic algorithm (GA) approached: an application of Turkey*, Energy and Buildings 2004, vol. 36 (2), 175-183

[205] Papadopoulos A. M., *State of the art in thermal insulation materials and aims for future developments*, Energy and Buildings 2005, vol. 37, 77-86

[206] Parekh A., *Development of archetypes of building characteristics libraries for simplified energy use evaluation of houses,* IBPSA, ninth international conference, Montreal, Canada, 2005

[207] Park C. D., El-Sharkawi A. M., Marks J. R., Atlas E. L., Damborg J. M., *Electric load forecast using an artificial neural network*, IEEE Transactions on Power Systems 1991, vol. 6 (2), 442-449

[208] Parti M., Parti C., *The total and appliance-specific conditional demand for electricity in the household sector*, The Bell Journal of Economics 1980, vol. 11 (1), 309-321

[209] Peng J., Lu L., Yang H., Ma T., *Comparative study of the thermal and power performance of a semi-transparent photovoltaic façade under different ventilation modes*, Applied Energy 2015, vol. 138, 572-583

[210] Perez-Lombard L., Ortiz J., Pout C., *A review on buildings energy consumption information,* Energy and Buildings 2008, vol. 40 (3), 394-398

[211] Perera A. T. D., Nik V. M., Mauree D., Scartezzini J.-L., *An integrated approach to design site specific distributed electrical hubs combining optimization, multi-criterion assessment and decision making*, Energy 2017, vol. 134, 103-120

[212] Perera A. T. D., Nik V. M., Mauree D., Scartezzini J.-L., *Electrical hubs: an effective way to integrate non-dispatchable renewable energy sources with minimum impact to the grid*, Applied Energy 2017, vol. 190, 232-248

[213] Quan S. J., Economou A., Grasl T., Yang P., *Computing energy performance of building density, shape and typology in urban context*, Energy Procedia 2014, vol. 61, 1602-1605

[214] Raffio G., Isambert O., Mertz G., Schreier C., Kissock K., *Targeting residential energy assistance*, Proceedings of energy sustainability conference 2007, 489-495

[215] Ramirez R., Sebold F., Mayer T., Ciminelli M., Abrishami M., *A building simulation palooza: the California CEUS project and DrCEUS*, IBPSA - ninth international conference, Montreal, Canada, 2005

[216] Rathood M. K., Banerjee J., *Thermal stability of phase change materials used in latent heat energy storage systems: A review*, Renewable and Sustainable Energy Reviews 2013, vol. 18, 246-258

[217] Raugei M., Frankl P., *Life cycle impacts and costs of photovoltaic systems: current state of the art and future outlooks*, Energy 2009, vol. 34 (3), 392-399

[218] Reed R., Bilos A., Wilkinson S., Shulte K. W., *Integrated Comparison of Sustainable Rating Tools*, Journal of Sustainable Real Estate 2009, vol. 1 (1), 1-22

[219] Reilly A., Kinnane O., *The impact of thermal mass on building energy consumption*, Applied Energy 2017, vol. 198, 108-121

[220] Reinhart F. C., Davila C. C., *Urban building energy modeling – A review of a nascent field*, Building and Environment 2016, vol. 97, 196-202

[221] Rezaie B., Esmailzadeh E., Dincer I., *Renewable energy options for buildings: Case studies*, Energy and Buildings 2011, vol. 43, 56-65

[222] Rezaei S. R., Shannigrahi S., Ramakrishna S., *A review of conventional, advanced and smart glazing technologies and materials for improving indoor environment*, Solar Energy Materials & Solar Cells 2017, vol. 159, 26-51

[223] Rodrigues S., Faria F. A., Ivaki A., Cafofo N., Chen X., Mata-Lima H., Morgado-Dias F., *Tesla Powerwall: Analysis of its use in Portugal and United States*, International Journal of Power and Energy Systems 2016, vol. 36 (1), 37-43

[224] Rupp R. F., Vasquez N. G., Lamberts R., *A review of human thermal comfort in the built environment*, Energy and Buildings 2015, vol. 105 ,178-205

[225] Saha G. P., Stephenson J., *A model of residential energy use in New Zealand*, Energy 1980, vol. 5 (2), 167-75

[226] Sandberg N. H., Sartori I., Heidrich O., Dawson R., Dascalaki E., Dimitriou S., Vimm-r T., Filippidou F., Stegnar G., Zavrl M. S., Brattebo H., *Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU*, Energy and Buildings 2016, vol. 132, 26-38

[227] Saravanan K., Sasithra S., *Review on Classification Based on Artificial Neural Networks*, International Journal of Ambient Systems and Applications 2014, vol. 2 (4), 11-18

[228] Sarbu I., Sebarcheivici C., *General review of ground-source heat pump systems for heating and cooling of buildings*, Energy and Buildings 2014, vol. 70, 441-454

[229] Sartori I., Sandberg N. H., Brattebo H., *Dynamic building stock modelling: General algorithm and exemplification for Norway*, Energy and Buildings 2016, vol. 132, 13-25

[230] Satake A., Ikegami H., Mitani Y., *Energy-saving operation and optimization of thermal comfort in thermal radiative cooling/heating system*, Energy Procedia 2016, vol. 100, 452-458

[231] Schilders W. H., van der Vorst H. A., Rommes J., *Model Oreder Reduction: Theory, Research Aspects and Applications,* The European Consortium for Mathematics in Industry (Springer) 2008, vol. 13

[232] Scrosati B., Garche J.*, Lithium batteries: Status, prospects and future*, Journal of Power Sources 2010, vol. 195, 2419-2430

[233] Sembroiz D., Careglio D., Ricciardi S. Fiore U., *Planning and operational energy optimization solutions for smart buildings*, Information Sciences 2019, vol. 476, 439-452

[234] Shaikh H. P., Nor B. M. N., Nallagownden P., Elamvazuthi I., Ibrahim T., *A review on optimized control systems for building energy and comfort management of smart sustainable buildings*, Renewable and Sustainable Energy Reviews 2014, vol. 34, 409-429

[235] Sharma A., Saxena A., Sethi M., Shree V., Varun, *Life cycle assessment of buildings: A review*, Renewable and Sustainable Energy Reviews 2011, vol. 15, 871-875

[236] Shimoda Y., Fujii T., Morikawa M., Mizuno M., *Residential end-use energy simulation at city scale*, Building and Environment 2004, vol. 39 (8), 959-967

[237] Shipley D., Todesco G., Adelaar M., *Modelling a nation of buildings: estimating energy efficiency potential for large building samples*, IBPSA Canada - eSim conference, Montreal, Canada, 2002

[238] Shorrock L. D., Dunster J. E., *The physically-based model BREHOMES and its use in deriving scenarios for the energy use and carbon dioxide emissions of the UK housing stock*, Energy Policy 1997, vol. 25 (12), 1027-1037

[239] Shubbak H. M., *Advances in solar photovoltaics: Technology review and patent trends*, Renewable and Sustainable Energy Reviews 2019, vol. 115

[240] Shukla N., Fallahi A., Kosny J., *Performance characterization of PCM impregnated gypsum board for building applications*, Energy Procedia 2012, vol. 30, 370-379

[241] Siller T., Kost M., Imboden D., *Long-term energy savings and greenhouse gas emission reductions in the Swiss residential sector*, Energy Policy 2007, vol. 35 (1), 529–539

[242] Simko T., Collins R., Beck F. A., *Edge Conduction in Vacuum Glazing*, Lawrence Berkeley National Laboratory, Energy & Environment Division, 1995

[243] Skórnóg M., *Klaster Energii Zbiornika Czorsztyńskiego*, '*Energetyka Wodna*' magazine, 2018, vol.3

[244] Snakin J-P. A., *An engineering model for heating energy and emission assessment the case of North Karelia, Finland*, Applied Energy 2000, vol. 67 (4), 353-381

[245] Sola A., Corchero C., Salom J., Sanmarti M., *Simulation Tools to Build Urban-Scale Energy Models: A Review*, Energies 2018, vol. 11, 3269

[246] Soto A. M., Jentsch M. F., *Comparison of prediction models for determining energy demand in the residential sector of a country*, Energy and Buildings 2016, vol. 128, 38-55

[247] Stachniewicz R., *Methods of estimation of the effective thickness of insulating outer walls*, Civil and Environmental Engineering 2012, vol. 3, 103-108

[248] Stathakis D., *How many hidden layers and nodes?*, International Journal of Remote Sensing 2008, vol. 30 (8), 2133-2147

[249] Stewart I. D., Oke T. R., *Local climate zones for urban temperature studies*, Bulletin of the American Meteorological Society 2012, vol. 93(12), 1879-1900

[250] Stotzer M., Hauer I., Richter M., Styczynski Z. A., *Potential of demand side integration to maximize use of renewable energy sources in Germany*, Applied Energy 2015, vol. 146 (15), 344-352

[251] Swan L. G., Ugursal V. I., *Modeling of end-use energy consumption in the residential sector: A review of modeling techniques*, Renewable and Sustainable Energy Reviews 2009, vol. 13, 1819-1835

[252] Taylor A. R., Miner M., *A metric for characterizing the effectiveness of thermal mass in building materials*, Applied Energy 2014, vol. 128, 156-163

[253] Theodoridou I., Karteris M., Mallinis G., Papadopoulos A. M., Hegger M., *Assessment of retrofitting measures and solar systems potential in urban areas using geographical information systems: application to a Mediterranean city*, Renewable and Sustainable Energy Reviews 2012, vol. 16, 6239-6261

[254] Tian Y., Zhao C. Y., *A review of solar collectors and thermal energy storage in solar thermal applications*, Applied Energy 2013, vol. 104, 538-593

[255] Tonn B. E., White D. L., *Residential electricity use, wood use, and indoor temperature: an econometric model*, Energy Systems and Policy 1988, vol. 12 (3), 151-165

[256] Tripathy M., Sadhu P. K., Panda S. K., *A critical review on building integrated photovoltaic products and their applications*, Renewable and Sustainable Energy Reviews 2016, vol. 61, 451-465

[257] Truong C. N., Naumann M., Karl R. C., Muller M., Jossen A., Hesse H. C., *Economics of Residential Photovoltaic Battery Systems in Germany: The Case of Tesla's Powerwall*, Batteries 2016, vol. 2 (2), 14

[258] Tuominen P., Holopainen R., Eskola L., Jokisalo J., Airaksinen M., *Calculation method and tool for assessing energy consumption in the building stock*, Building and Environment 2014, vol. 75, 153-160

[259] Uddin M., Romlie F. M., Abdullah F. M., Halim A. S., Bakar H. A. A., Kwang Ch. T., *A review on peak load shaving strategies*, Renewable and Sustainable Energy Reviews 2018, vol. 82, 3323-3332

[260] Urge-Vorsatz D., Novikova A., Koppel S., Boza-Kiss B., *Bottom-up assessment of potentials and costs of CO2 emission mitigation in the buildings sector: insights into the missing elements*, Energy Efficiency 2009, vol. 2 (4), 293–316

[261] Vigna I., Pernetti R., Pasut W., Lollini R., *New domain for promoting energy efficiency: Energy Flexible Building Cluster*, Sustainable Cities and Society 2018, vol. 38, 526-533

[262] Voll H., Seinre E., *A method of optimizing fenestration design for daylighting to reduce heating and cooling loads in offices*, Journal of Civil Engineering and Management 2014, vol. 20 (5), 714-723

[263] Wang E., Fung A. S., Qi C., Leong W. H., *Performance prediction of a hybrid ground-source heat pump system*, Energy and Buildings 2012, vol. 47, 600-611

[264] Webb A. L., *Energy retrofits in historic and traditional buildings: A review of problems and methods*, Renewable and Sustainable Energy Reviews 2017, vol. 77, 748-759

[265] Weir G., Muneer T., *Energy and environmental impact analysis of double-glazed windows*, Energy Conversion and Management 1998, vol. 39 (3-4), 243-256

[266] Wit de S., Augenbroe G., *Analysis of uncertainty in building design evaluations and its implications*, Energy and Buildings 2002, vol. 34, 951-958

[267] Witte M. J., Henninger R. H., Crawley D. B., *Experience Testing EnergyPlus with the ASHRAE 1052-RP Building Fabric Analytical Tests*, Proceedings of SimBuild Conference 2004

[268] Witte M. J., Henninger R. H., Glazer J., Crawley D. B., *Testing and Validation of a New Building Energy Simulation Program*, Proceedings of Building Simulation 2001

[269] Yang F., Jiang Z., *Urban building energy modelling and urban design for sustainable neighbourhood development – A China perspective*, IOP Conf. Series: Earth and Environmental Science 2019, vol. 329

[270] Yang J., Rivard H., Zmeureanu R., *Building energy prediction with adaptive artificial neural networks*, IBPSA - ninth international conference, Montreal, Canada, 2005

[271] Yang L., Yan H., Lam J. C., *Thermal comfort and building energy consumption implications – A review*, Applied Energy 2014, vol. 115, 164-173

[272] Yao R., Steemers K., *A method of formulating energy load profile for domestic buildings in the UK*, Energy and Buildings 2005, vol. 37 (6), 663-671

[273] Zhai X. Q., Qu M., Yu X., Yang Y., Wang R. Z., *A review for the applications and integrated approaches of ground-coupled heat pump systems*, Renewable and Sustainable Energy Reviews 2011, vol. 15, 3133-3140

[274] Zhang W., Liu S., Li N., Xie H., Li X., *Development forecast and technology roadmap analysis of renewable energy in buildings in China*, Renewable and Sustainable Energy Reviews 2015, vol. 49, 395-402

[275] Zhang X., Lovati M., Vigna I., Widen J., Han M., Gal C., Feng T., *A review of urban energy systems at building cluster level incorporating renewable-energy-source (RES) envelope solutions*, Applied Energy 2018, vol. 230, 1034-1056

[276] Zhang X., Zhao X., Smith S., Xu J., Yu X., *Review of R&D progress and practical application of the solar photovoltaic/thermal (PV/T) technologies*, Renewable and Sustainable Energy reviews 2012, vol. 16, 599-617

[277] Zhon X., Hong T., Yan D., *Comparison of Building Energy Modeling Programs: HVAC Systems*, Ernest Orlando Lawrence, Berkeley National Laboratory 2013

[278] Zhu D., Hong T., Wang C., *A detailed loads comparison of three building energy modelling programs: EnergyPlus, DeST and DOE-2.1E*, Building Simulation 2013, vol. 6, 323-335

[279] Zygmunt M., Gawin D., *Analysis of applying various demand side management techniques for reduction of cooling power demand peak for the group of public utility buildings*, Journal of Civil Engineering, Environment and Architecture 2016, vol. 63 (4), 581-588

[280] Zygmunt M., Gawin D., *Analysis of energy efficiency and thermal comfort for an office building complex located in Poland – a case study*, IOP Conference Series: Materials Science and Engineering 2018, vol. 415

[281] Zygmunt M., Gawin D., *Application of ANN for analysing a neighbourhood of single-family houses constituting an Energy Cluster*, MATEC Web of Conferences 2019, vol. 282

[282] Zygmunt M., Gawin D., *Potential of Renewable Energy Sources usage in an energy demand of a single-family houses neighbourhood, constituting an Energy Cluster – a case study*, E3S Web of Conferences 2020, vol. 172

[283] Zygmunt M., Gawin D., *Wind farm potential for electrical Energy supply to a neighbourhood of single-family houses located at the Polish Baltic seaside*, Open Access Proceedings E3S Web of Conferences 2018, vol. 49

[284] Zygmunt M., Piczulski M., *Economic, environmental and social aspects of buildings' refurbishment – a case study*, Scientific Review – Engineering and Environmental Sciences 2018, vol. 27 (4), 567-578

SCIENTIFIC REPORTS

[285] Amanatidis G., *European policies on climate and energy towards 2020, 2030 and 2050,* The European Parliament, Brussels 2019

[286] ASHARE, *ASHARE Handbook: Heating, Ventilation and Air-conditioning Applications*, ASHARE 2019

[287] Cambridge architectural research, *Cambridge Housing Model and User Guide*, Department of Energy & Climate Change 2010

[288] Danish Building Research Institute (SBI) and 3XN Architects (GXN), *Guide to Sustainable Building Certification*, 2018

[289] Ellen Macarthur Foundation, *Towards the Circular Economy – Economic and business rationale for an accelerated transition*, 2013

[290] European Commission*, A Roadmap for moving to a competitive low carbon economy in 2050,* 2011

[291] Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), *Strategies for Efficient Houses Plus – Principles and examples of energy-generating buildings*, 2016

[292] Gervasio H., Dimova S., *JRC TECHNICAL REPORTS – Model for Life Cycle Assessment (LCA) of buildings*, European Commission, 2018

[293] Heaps C., *User Guide for LEAP*, Stockholm Environment Institute−U.S. Center, Somerville, USA, 2010

[294] Huang Y., Broderick J., *A bottom-up engineering estimate of the aggregate heating and cooling loads of the entire US building stock (Report LBNL-46303),* Lawrence Berkeley National Laboratory, 2000

[295] Institut Wohnen und Umwelt GmbH, *Monitor Progress Towards Climate Targets in European Housing Stocks – Main results of the EPISCOPE Project – Final Project Report*, 2016

[296] International Atomic Energy Agency (IAEA), *Model for Analysis of Energy Demand (MAED-2) User's Manual*, Austria, 2006

[297] International Renewable Energy Agency (IRENA), *Electricity Storage and Renewable: Costs and Markets to 2030*, 2017

[298] International Renewable Energy Agency (IRENA)*, Global Energy Transformation – a roadmap to 2050*, 2019

[299] *International Technology Roadmap for Photovoltaic – Results 2017*, 2018

[300] Koomey J.G., Brown R.E., Richey R., Johnson F.X., Sanstad A.H., Shown L., *Residential Sector End-use Forecasting with Epri-reeps 2.1: Summary Input Assumptions and Results*, Lawrence Berkeley Laboratory, Berkley, USA, 1995

[301] Macuk R., Maćkowiak J., Rubczyński A., *Energy transition in Poland – Edition 2018*, 2018

[302] Michiorri A., Pelaez A. M., Bessa R., *Energy Storage Domain Roles & Classification. A Report*, European Union's Horizon 2020 Research and Innovation Programme 2015

[303] Ministerstwo Aktywów Państwowych (MAP)*, Koncepcja funkcjonowania Klastrów Energii w Polsce,* 2016

[304] Popławski T., *Forecast demand for energy and peak power for Poland to the year 2040*, 2014

[305] Ram M., Bogdanov D., Aghahosseini A., Gulagi A., Oyewo A.S., Child M., Caldera U., Sadovskaia K., Farfan J., Barbosa LSNS., Fasihi M., Khalili S., Fell H.-J., Breyer C., *Global Energy System based on 100% Renewable Energy – Energy Transition in Europe Across Power, Heat, Transport and Desalination Sectors.* Study by LUT University and Energy Watch Group, 2018

[306] Renewables 2017 (REN21 – Renewable Energy Policy Network for the 21st Century), *Global Status Reporting. Renewable Energy Policy Network for the 21st Century*, 2018

[307] The European Commission, *A Clean Planet for all – A European strategic long-term vision for a prosperous, modern, competitive and climate natural economy*, Brussels, 2018

[308] The European Commission, *A Roadmap for moving to a competitive low carbon economy in 2050*, Brussels, 2011

[309] The European Commission, *Energy Roadmap 2050*, Brussels, 2011

[310] The European Commission, *Going climate-neutral by 2050 – A strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy*, Brussels 2019

[311] The European Heat Pump Association (EHPA), *European Heat Pump Statistics – Outlook 2009*, 2009

[312] The Institute of Environmental Economics (IES), *Energy Efficiency in Poland – 2017 review*, 2017

[313] The Intelligent Energy Europe (IEE)*, EPISCOPE – Project Information, 2013*

[314] The National Centre for Emissions Management – KOBiZE*, Wskazniki emisji zanieczyszczen ze spalania paliw,* Warsaw 2015

[315] The National Energy Conservation Agency (NAPE)*, Polish building typology – TABULA – Scientific report,* 2012

[316] The PSE *(pol. PSE – Polskie Sieci Elektroenergetyczne)*, *Polish power system operation statistic of 2018* (title in Polish: *Zestawianie danych ilościowych dotyczących funkcjonowania KSE w 2018 roku*), 2018

[317] The Statistics Poland (GUS), *Demographic Yearbook of Poland*, 2019

[318] The Statistics Poland (GUS), *Housing Construction I-IV quarter 2014*, 2015

[319] The Statistics Poland (GUS), *Housing Construction I-IV quarter 2017*, 2017

[320] The U.S. Energy Information Administration (EIA), *International Energy Outlook 2017*, 2017

[321] The World Commission on Environment and Development, *Our common future*, Oxford: Oxford University Press 1987

[322] United Nations, Department of Economic and Social Affairs, *World Population Prospects: The 2019 Revision*, 2019

[323] U.S. Department of Energy*, EnergyPlus Version 9.2.0 Documentation – Engineering Reference,* 2019

[324] U.S. Department of Energy*, EnergyPlus Version 9.2.0 Documentation – Getting Started,* 2019

[325] U.S. Department of Energy*, EnergyPlus Version 9.2.0 Documentation – Input Output Reference,* 2019

[326] U.S. Department of Energy*, EnergyPlus Version 9.2.0 Documentation – Output Details and Examples,* 2019

DIRECTIVES AND NORMS

[327] ANSI/ASHRAE Standard 55-2013, *Thermal Environment Conditions for Human Occupancy*, American Society of Heating, Refrigerating, and Air-conditioning Engineers Inc., 2017

[328] BS EN 15603, *Energy performance of buildings. Overall energy use and definition of energy ratings*, 2008

[329] BS EN 15978 *Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method*, 2011

[330] BS 8001, *Framework for implementing the principles of the circular economy in organization. Guide*, 2017

[331] Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020

[332] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC

[333] Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community

[334] Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006

[335] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings

[336] Dz.U. 2008 nr 223 poz. 1459, *Ustawa z dnia 21 listopada 2008r. o wspieraniu termomodernizacji i remontów*, 2008

[337] Dz.U. 2009 nr 43 poz. 346, *Rozporządzenie Ministra Infrastruktury z dnia 17 marca 2009 r. w sprawie szczegółowego zakresu i form audytu energetycznego oraz części audytu remontowego, wzorów kart audytów, a także algorytmu oceny opłacalności przedsięwzięcia termomodernizacyjnego*, 2009

[338] Dz.U. 2015 poz. 376, *Rozporządzenie Ministra Infrastruktury i Rozwoju z dnia 27 lutego 2015r. w sprawie metodologii wyznaczania charakterystyki energetycznej budynku lub części budynku oraz świadectwa charakterystyki energetycznej*, 2015

[339] Dz. U. 2015 poz. 478, *Ustawa z dnia 20 lutego 2015r. o odnawialnych źródłach energii*, 2015

[340] Dz.U. 2015 poz. 1606, *Rozporządzenie Ministra Infrastruktury i Rozwoju z dnia 3 września 2015 r. zmieniające rozporządzenie w sprawie szczegółowego zakresu i form audytu energetycznego oraz części audytu remontowego, wzorów kart audytów, a także algorytmu oceny opłacalności przedsięwzięcia termomodernizacyjnego*, 2015

[341] Dz.U. 2016 poz. 831, *Ustawa z dnia 20 maja 2016 r. o efektywności energetycznej*, 2016

[342] Dz.U. 2016 poz. 925, *Ustawa z dnia 22 czerwca 2016 r. o zmianie ustawy o odnawialnych źródłach energii oraz niektórych innych ustaw*, 2016

[343] Dz.U. 2016 poz. 961, Ustawa z dnia 20 maja 2016r. *o inwestycjach w zakresie elektrowni wiatrowych*, 2016

[344] Dz.U. 2017 poz. 1912, *Rozporządzenie Ministra Energii z dnia 5 października 2017 r. w sprawie szczegółowego zakresu i sposobu sporządzania audytu efektywności energetycznej oraz metod obliczania oszczędności energii*, 2017

[345] Dz. U. 2018 poz.9, *Ustawa z dnia 8 grudnia 2017r. o rynku mocy*, 2017

[346] Dz.U. 2019 poz. 1065, *Obwieszczenie Ministra Inwestycji i Rozwoju z dnia 8 kwietnia 2019 r. w sprawie ogłoszenia jednolitego tekstu rozporządzenia Ministra Infrastruktury w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie*, 2019

[347] EN 15459 *Energy performance of buildings – Economic evaluation procedure for energy systems in buildings*, 2007

[348] EN ISO 15927-4 *Hygro-thermal performance of buildings - Calculation and presentation of climatic data - Part 4 Data for assessing the annual energy for cooling and heating systems*, 2005

[349] IEA/ECBCS Annex 39, *Vacuum Insulation in the Building Sector. Systems and Applications,* 2005

[350] IEA/ECBCS Annex 39, *Vacuum Insulation Panels. Study on VIP-components and Panels for Service Life. Prediction of VIP in Building Applications (Subtask A)*, 2005

[351] ISO 12665, *Light and Lighting Basic Terms and Criteria for Specifying Lighting Requirements*, 2011

[352] ISO 14040 *Environmental management – Life cycle assessment – Principles and framework*, 2006

[353] ISO 14042 *Environmental management – Life cycle assessment – Life cycle impact assessment*, 2000

[354] ISO 14043 *Environmental management – Life cycle assessment – Life cycle interpretation*, 2000

[355] ISO 14044 *Environmental management – Life cycle assessment – Requirements and guidelines*, 2006

[356] ISO 14047 *Environmental management – Life cycle assessment – Illustrative examples on how to apply ISO 14044 to impact assessment situations*, 2012

[357] ISO 14048 *Environmental management – Life cycle assessment – Data documentation format*, 2002

[358] ISO 6946, *Building components and building elements – Thermal resistance and thermal transmittance – Calculation methods*, 2017

[359] PN-EN 12831-1:2017-08, *Charakterystyka energetyczna budynków – Metoda obliczania projektowego obciążenia cieplnego – Część 1: Obciążenie cieplne*, 2017

[360] PN-EN 15643-1 *Sustainability of construction works. Sustainability assessment of buildings. General framework*, 2010

[361] PN-EN 15643-2 *Sustainability of construction works. Assessment of buildings. Framework for the assessment of environmental performance*, 2012

[362] PN-EN 15643-3 *Sustainability of construction works. Assessment of buildings. Framework for the assessment of social performance*, 2012

[363] PN-EN 15643-4 *Sustainability of construction works. Assessment of buildings. Framework for the assessment of economic performance*, 2012

[364] PN-EN 15804 *Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products*,2012

[365] PN-EN 15978 *Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method*,2012

[366] PN-EN 16309 *Sustainability of construction works. Assessment of social performance of buildings. Calculation methodology*, 2014

WEB SOURCES

[367] *BREEAM Certification*, https://www.breeam.com (accessed on 15.06.2019)

[368] *Build Desk company*, http://www.builddesk.co.uk (accessed on: 01.02.2019)

[369] *Building Energy Software Tools (BEST Directory)*, https://www.buildingenergysoftwaretools.com (accessed on 15.06.2019)

[370] *Centrum Informacji o Rynku Energii*, http://www.cire.pl (accessed on 10.09.2019)

[371] *Czortynski Energy Cluster,* https://ppkpodhale.pl/pl/ (accessed on 15.06.2019)

[372] *Design Builder,* https://designbuilder.co.uk (accessed on 01.02.2019)

[373] *DGNB System,* https://www.dgnb-system.de/en/ (accessed on 15.06.2019)

[374] *DOE-2*, http://www.doe2.com (accessed on 01.02.2019)

[375] *EIT RawMaterials – Connecting matters*, https://eitrawmaterials.eu (accessed on 01.02.2020)

[376] *Enerdata – Global Energy Statistical Yearbook*, https://yearbook.enerdata.net (accessed on 10.12.2019)

[377] *Energy Regulatory Office (in Polish: Urząd Regulacji Energetycznej, URE)*, https://www.ure.gov.pl/en (accessed on 10.08.2019)

[378] *EnergyPlus*, https://energyplus.net (accessed on 01.02.2019)

[379] *EPISCOPE and TABULA website*, https://episcope.eu/index.php?id=97 (accessed on: 01.02.2019)

[380] *ESP-r*, http://www.esru.strath.ac.uk/Programs/ESP-r.htm (accessed on 01.02.2019)

[381] *EU Science Hub – Photovoltaic Geographical Information System (PVGIS)*, https://ec.europa.eu/jrc/en/pvgis (accessed on 15.06.2019)

[382] *European Air Quality Index (EEA)*, https://airindex.eea.europa.eu/Map/AQI/Viewer/ (accessed on 01.02.2019)

[383] *FINO 2 – Research Platform in the Baltic Sea*, https://www.fino2.de/en/ (accessed on 01.02.2019)

[384] *Fraunhofer Institute for Building Physics (IBP)*, https://www.ibp.fraunhofer.de/en.html (accessed on 15.02.2020)

[385] *Green Building Council Australia*, https://new.gbca.org.au (accessed on 15.06.2019)

[386] *HOMER Energy website,* https://www.homerenergy.com/index.html (accessed on 01.02.2019)

[387] *International Renewable Energy Agency (IRENA),* https://www.irena.org (accessed on 10.10.2019)

[388] *Lawrence Berkeley National Laboratory – Berkeley Lab,* https://www.lbl.gov (accessed on 01.02.2019)

[389] *MathWorks website*, https://www.mathworks.com (accessed on 01.02.2019)

[390] *Ministerstwo Aktywów Państwowych (MAP)*, https://www.gov.pl/web/aktywa-panstwowe (accessed on 15.06.2019)

[391] *Ministerstwo Funduszy i Polityki Regionalnej (MFiPR)*, https://www.gov.pl/web/inwestycje-rozwoj (accessed on 15.06.2019)

[392] *MIT Sustainable Design Lab*, http://web.mit.edu/sustainabledesignlab/projects/umi/index.html (accessed on 01.02.2019)

[393] *National Energy Conservation Agency (in Polish: Narodowa Agencja Poszanowania Energii, NAPE),* https://nape.pl/en/home (accessed on: 01.02.2019)

[394] *OpenStudio*, https://www.openstudio.net (accessed on 01.02.2019)

[395] *Our World in Data*, https://ourworldindata.org/energy (accessed on 10.09.2019)

[396] *Polish Institute of Meteorology and Water Management – National Research Institute* (in Polish: *Instytut Meteorologii i Gospodarki Wodnej – Panstwowy Instytut Badawczy, IMGW*), https://www.imgw.pl

[397] *Polskie Sieci Elektroenergetyczne (PSE S.A.)*, https://www.pse.pl/web/pse-eng (accessed on 10.08.2019)

[398] *SketchUp software,* https://www.sketchup.com (accessed on 01.02.2019)

[399] *TABULA WebTool,* http://webtool.building-typology.eu/#bm (accessed on 01.02.2019)

[400] *Tesla – Powerwall – The Tesla Home Battery*, https://www.tesla.com/powerwall (accessed on 15.02.2020)

[401] *The 4C Offshore,* http://www.4coffshore.com (accessed on 01.02.2019)

[402] *The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)*, https://www.ashrae.org (accessed on 01.02.2019)

[403] *The CityBES software*, https://citybes.lbl.gov (accessed on 01.02.2019)

[404] *The CitySim software*, https://www.epfl.ch/labs/leso/transfer/software/citysim/ (accessed on 01.02.2019)

[405] *The Energy Action*, http://energyaction-static.s3-website-eu-west-1.amazonaws.com/index.html (accessed on: 01.02.2019)

[406] *The Energy in Buildings and Communities Programme (EBC)*, https://www.iea-ebc.org (accessed on 01.02.2019)

[407] *The European Commission*, http://ec.europa.eu (accessed on 01.02.2019)

[408] *The European Environment Agency (EEA)*, https://www.eea.europa.eu (accessed on 10.10.2019)

[409] *The Federal Ministry for Economic Affairs and Energy (BMWI)*, https://www.bmwi.de (accessed on 01.02.2019)

[410] *The Geoportal*, https://geoportal.gov.pl (accessed on 01.11.2020)

[411] *The Head Office of Geodesy and Cartography*, http://www.gugik.gov.pl (accessed on 01.11.2020))

[412] *The Institute of Environmental Economics (IES)*, http://iee.org.pl/index.php/institute-of-environmental-economics-3/ (accessed on 10.10.2018)

[413] *The International Energy Agency (IEA)*, https://www.iea.org (accessed on 01.02.2019)

[414] *The KlasGRID – Agreement of Polish Energy Clusters Cooperation*, http://www.klasgrid.pl/en/ (accessed on 15.06.2019)

[415] *The National Fund for Environmental Protection and Water Management (NFEP&WM)*, http://www.nfosigw.gov.pl/en/ (accessed on 15.06.2019)

[416] *The National Renewable Energy Laboratory (NREL)*, https://www.nrel.gov (accessed on 01.02.2019)

[417] *The National Security Bureau of Poland*, https://www.bbn.gov.pl (accessed on 01.02.2019)

[418] *The Natural Resources Defense Council, Inc. (NRDC), the Institute for Market Transformation (IMT), City Energy Project 2017*, https://www.cityenergyproject.org (accessed on 10.10.2019)

[419] *The populationof.net – demographic and population data online*, https://www.popula-tionof.net/com/poland/ (accessed on 10.08.2019)

[420] *The Statistics Poland (GUS) website,* https://stat.gov.pl/en/ (accessed on 01.02.2019)

[421] *The QGIS – Geographical Information System*, https://www.qgis.org/en/site/ (accessed on 01.02.2019)

[422] *The Rhinoceros software*, https://www.rhino3d.com (accessed on 01.02.2019)

[423] *The World Commission on Environmental and Development*, https://sustainabledevelopment.un.org/milestones/wced (accessed on 15.02.2020)

[424] *TRNSYS*, http://www.trnsys.com (accessed on 01.02.2019)

[425] *U.S. Department of Energy,* https://www.energy.gov (accessed on 01.02.2019)

[426] *U.S. Energy Information Administration (EIA)*, https://www.eia.gov (accessed on 10.09.2019)

[427] *U.S. Green Building Council,* https://www.usgbc.org (accessed on 15.06.2019)

APPENDIX 1 – DETAILED DATA OF POLISH REPRESENTATIVE SINGLE-FAMILY HOUSES

	RSFH_1	RSFH_2	RSFH_3	RSFH_4	RSFH_5	RSFH_6	RSFH_7
BUILT PERIOD	before 1945	1946-1966	1967-1985	1986-1992	1993-2002	2003-2009	after 2009
A_{TOT} [m^2]	84.00	115.00	154.00	160.00	180.00	203.00	220.00
A_o [m^2]	72.00	98.20	128.60	140.30	160.10	175.50	188.20
V_o [m^3]	180.50	245.50	330.80	408.00	448.30	501.20	540.00
A/V [1/m]	1.19	1.16	1.06	0.96	0.97	0.95	0.94
STOREYS	2	2	2	2	2	2	2
H [m]	2.51	2.50	2.57	2.91	2.80	2.86	2.87
ROOF TYPE	TR	TR	TR	TR	TR	TR	TR
ATTIC CONDITIONS	UC	UC	UC	UC	UC	UC	UC
ATTACHED NEIGHBOURS	DB	DB	DB	DB	DB	DB	DB
A_{WALL} [m^2]	84.50	103.60	105.20	108.50	118.80	124.60	144.50
A_{ROOF} [m^2]	48.23	76.30	77.40	82.30	99.30	106.80	125.50
A_{WINDOW} [m^2]	13.00	20.60	23.10	24.10	35.70	38.40	47.40
A_{N_WINDOW} [m^2]	0.65	1.00	1.30	4.30	2.00	1.98	2.28
A_{S_WINDOW} [m^2]	5.20	8.20	9.20	9.60	14.20	15.30	18.90
A_{W_WINDOW} [m^2]	3.25	5.20	5.70	6.00	8.80	11.52	12.00
A_{E_WINDOW} [m^2]	3.90	6.20	6.90	4.20	10.70	15.30	14.22

A_{DOOR} [m²]	2.00	2.00	2.00	2.00	2.00	2.00	2.00
U_{WALL} [W/m²K]	1.70	1.70	1.18	1.40	0.50	0.28	0.29
U_{ROOF} [W/m²K]	0.85	0.75	0.65	0.50	0.50	0.40	0.35
U_{FLOOR} [W/m²K]	2.35	1.95	1.75	1.50	1.10	0.70	0.60
$U_{WINDOWS}$ [W/m²K]	5.15	5.15	2.75	2.70	1.70	1.30	1.20
SHGC [-]	0.85	0.85	0.75	0.73	0.77	0.77	0.50
U_{DOORS} [W/m²K]	5.10	4.50	4.00	3.60	2.50	1.80	1.70
THERMAL BRIDGING IMPACT	high	high	high	medium	medium	medium	medium
VENTILATION SYSTEM	natural	natural	natural	natural	natural	natural	natural
n_{ACH} [1/h]	0.40	0.40	0.40	0.40	0.40	0.40	0.40
n_{INF} [1/h]	0.40	0.40	0.20	0.20	0.20	0.20	0.20
HEATING SYSTEM COP	0.59	0.59	0.59	0.86	0.87	0.87	0.87
HEATING SYSTEM FUEL	coal	coal	coal	gas	gas	gas	gas
DHW COP	0.59	0.59	0.59	0.59	0.70	0.70	0.70
DHW FUEL	electricity	electricity	electricity	electricity	gas	gas	gas
EK [kWh/m²a]	348.00	327.00	253.00	186.00	160.00	140.00	141.00

Where: **TR** – tiled roof with inclination not lower than 30deg, **UC** – attic completely unconditioned, **DB** – detached building (stand-alone), A_{TOT} – total building area, A_o – heated area, V_o – volume, **A/V** – shape factor, **h** – height, A_{WALL} – total area of exterior walls, A_{ROOF} – total roof area, A_{WINDOW} – total area of windows, A_{N_WINDOW} – total area windows on North façade, A_{S_WINDOW} – total area windows on South façade, A_{W_WINDOW} – total area windows on West façade, A_{E_WINDOW} – total area windows on East façade, A_{ROOR} – total area of exterior doors, U_{WALL} – thermal transmittance of exterior walls, U_{ROOF} – thermal transmittance of a roof, U_{FLOOR} – thermal transmittance of the ground floor, $U_{WINDOWS}$ – thermal transmittance of windows, **SHGC** – solar heat gain coefficient (windows), U_{DOORS} – thermal transmittance of exterior doors, n_{ACH} – base ventilation airflow, n_{INF} – infiltration airflow, **EK** – end-use energy factor

APPENDIX 2 – DETAILED DATA OF DEFINED COMPUTER MODELS OF POLISH REPRESENTATIVE SINGLE-FAMILY HOUSES

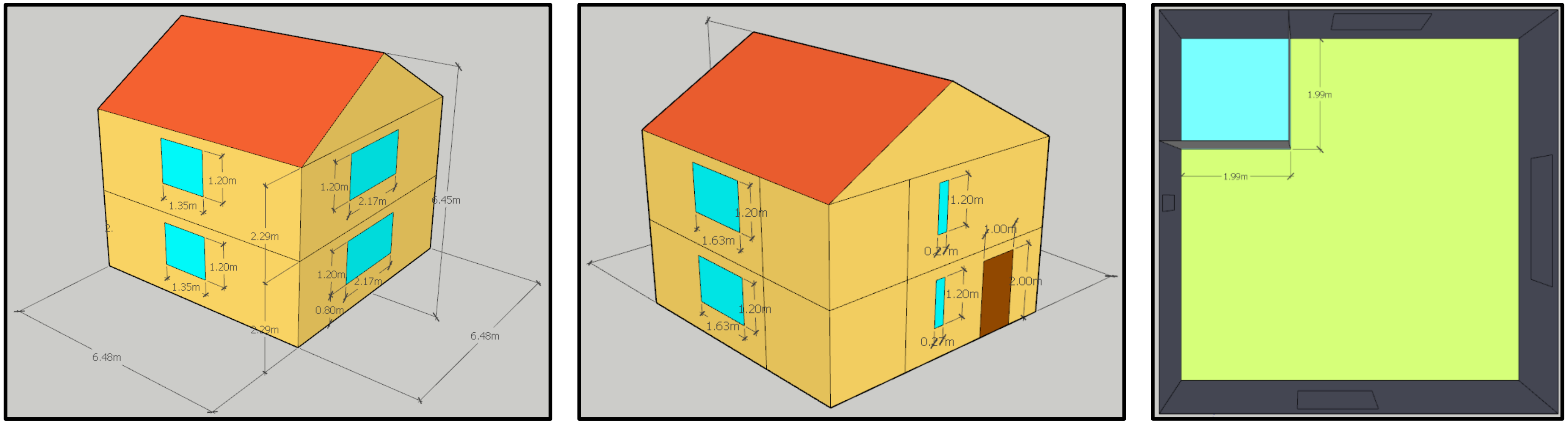
	RSFH_1	RSFH_2	RSFH_3	RSFH_4	RSFH_5	RSFH_6	RSFH_7
A_G [m^2]	42.00	57.50	77.00	80.00	90.00	101.50	110.00
A [m]	6.48	7.58	8.77	8.94	9.49	10.07	10.49
B [m]	6.48	7.58	8.77	8.94	9.49	10.07	10.49
A_O [m^2]	78.90	99.20	134.31	139.92	155.12	172.04	188.49
V_O [m^3]	180.50	245.50	330.80	408.00	448.30	501.20	540.00
A/V [1/m]	1.19	1.16	1.06	0.96	0.97	0.95	0.95
STOREYS	2	2	2	2	2	2	2
H [m]	2.29	2.47	2.46	2.92	2.89	2.91	2.86
ROOF TYPE	TR	TR	TR	TR	TR	TR	TR
ROOF SLOPE [DEG]	30	30	30	30	30	30	30
A_{WALL} [m^2]	118.62	150.12	172.89	208.65	219.34	234.80	240.37
A_{ROOF} [m^2]	42.00	57.50	77.00	80.00	90.00	101.50	110.00
A_{WINDOW} [m^2]	13.00	20.60	23.10	24.10	35.70	38.40	47.40
$H_{WINDOWS}$ [m]	1.40	1.40	1.40	1.40	1.40	1.40	1.40
A_{N_WINDOW} [m^2]	0.65	1.00	1.30	4.30	2.00	1.98	2.28
A_{S_WINDOW} [m^2]	5.20	8.20	9.20	9.60	14.20	15.30	18.90
A_{W_WINDOW} [m^2]	3.25	5.20	5.70	6.00	8.80	11.52	12.00

A_{E_WINDOW} [m²]	3.90	6.20	6.90	4.20	10.70	15.30	14.22
A_{DOOR} [m²]	2.00	2.00	2.00	2.00	2.00	2.00	2.00
U_{WALL} [W/m²K]	1.70	1.70	1.18	1.40	0.50	0.28	0.29
U_{ROOF} [W/m²K]	0.85	0.75	0.65	0.50	0.50	0.40	0.35
U_{FLOOR} [W/m²K]	2.35	1.95	1.75	1.50	1.10	0.70	0.60
$U_{WINDOWS}$ [W/m²K]	5.15	5.15	2.75	2.70	1.70	1.30	1.20
SHGC [-]	0.85	0.85	0.75	0.73	0.77	0.77	0.50
U_{DOORS} [W/m²K]	5.10	4.50	4.00	3.60	2.50	1.80	1.70
VENTILATION SYSTEM	natural	natural	natural	natural	natural	natural	natural
N_{ACH} [1/h]	0.40	0.40	0.40	0.40	0.40	0.40	0.40
N_{INF} [1/h]	0.40	0.40	0.20	0.20	0.20	0.20	0.20
HEATING SYSTEM COP	0.59	0.59	0.59	0.87	0.87	0.87	0.87
HEATING SYSTEM FUEL	coal	coal	coal	gas	gas	gas	gas
DHW COP	0.59	0.59	0.59	0.59	0.70	0.70	0.70
DHW FUEL	electricity	electricity	electricity	electricity	gas	gas	gas

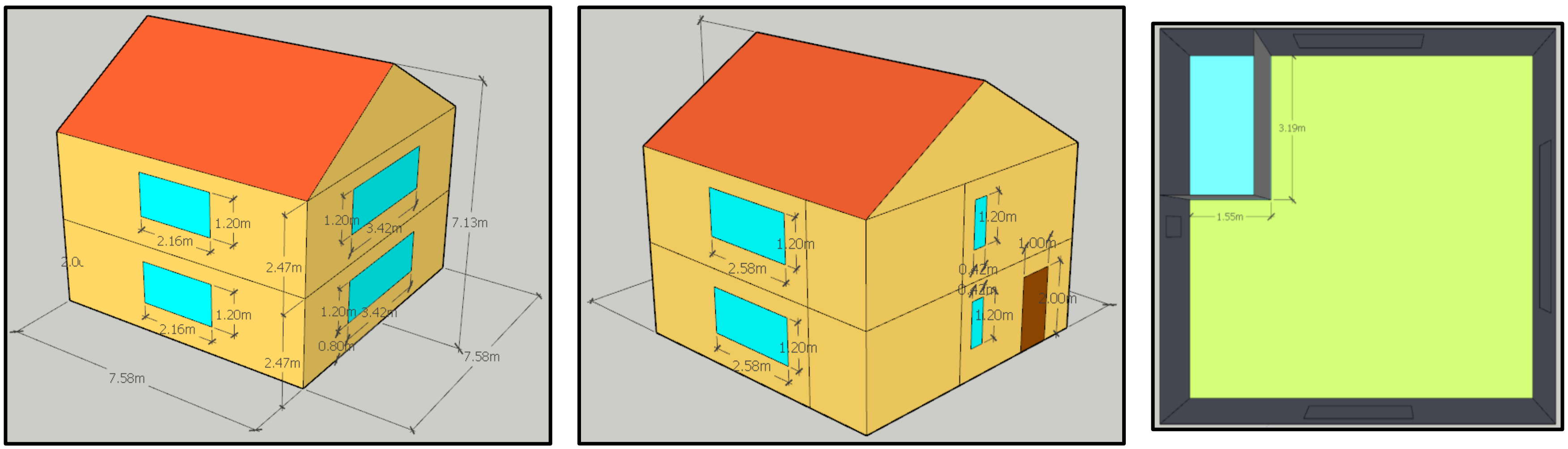
Where: **TR** – tiled roof with inclination not lower than 30deg, **A_G** – gross covered area, **A** – building length, **B** – building width, **A_o** – heated area, **V_o** – volume, **A/V** – shape factor, **H** – height, **A_{WALL}** – total area of exterior walls, **A_{ROOF}** – total roof area**, A_{WINDOW}** – total area of windows**, A_{N_WINDOW}** – total area windows on North façade**, A_{S_WINDOW}** – total area windows on South façade, **A_{W_WINDOW}** – total area windows on West façade**, A_{E_WINDOW}** – total area windows on East façade**, A_{ROOR}** – total area of exterior doors**, U_{WALL}** – thermal transmittance of exterior walls, **U_{ROOF}** – thermal transmittance of a roof, **U_{FLOOR}** – thermal transmittance of the ground floor, **$U_{WINDOWS}$** – thermal transmittance of windows, **SHGC** – solar heat gain coefficient (windows), **U_{DOORS}** – thermal transmittance of exterior doors, **N_{ACH}** – base ventilation airflow, **N_{INF}** – infiltration airflow, **EK** – end-use energy factor

APPENDIX 3 – GEOMETRY OF RSFBS DEFINED BY MEANS OF THE *ENERGY PLUS* SOFTWARE

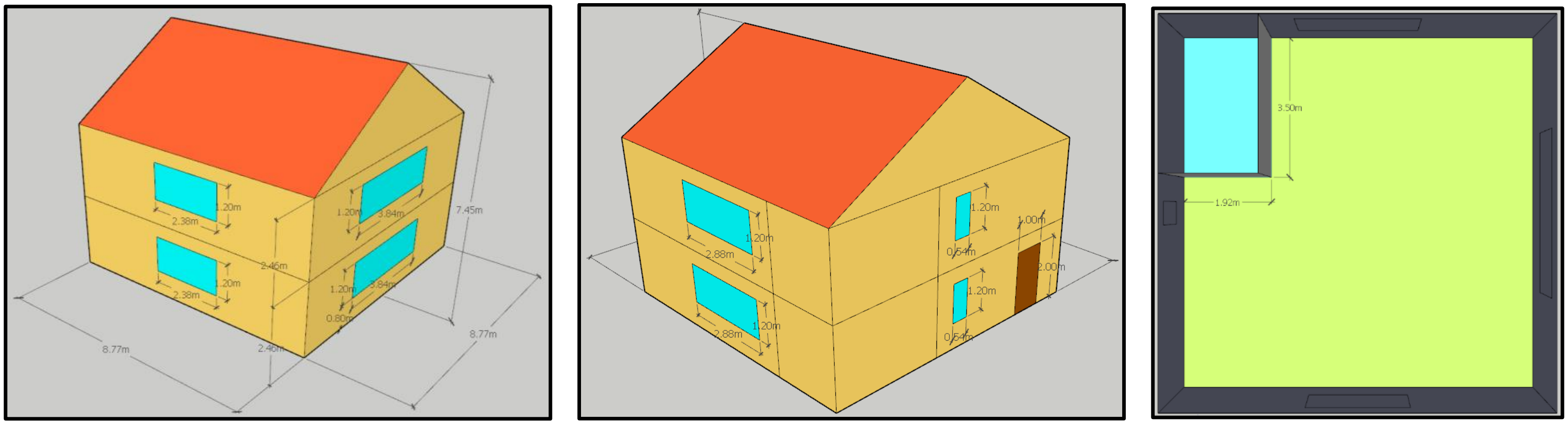
A



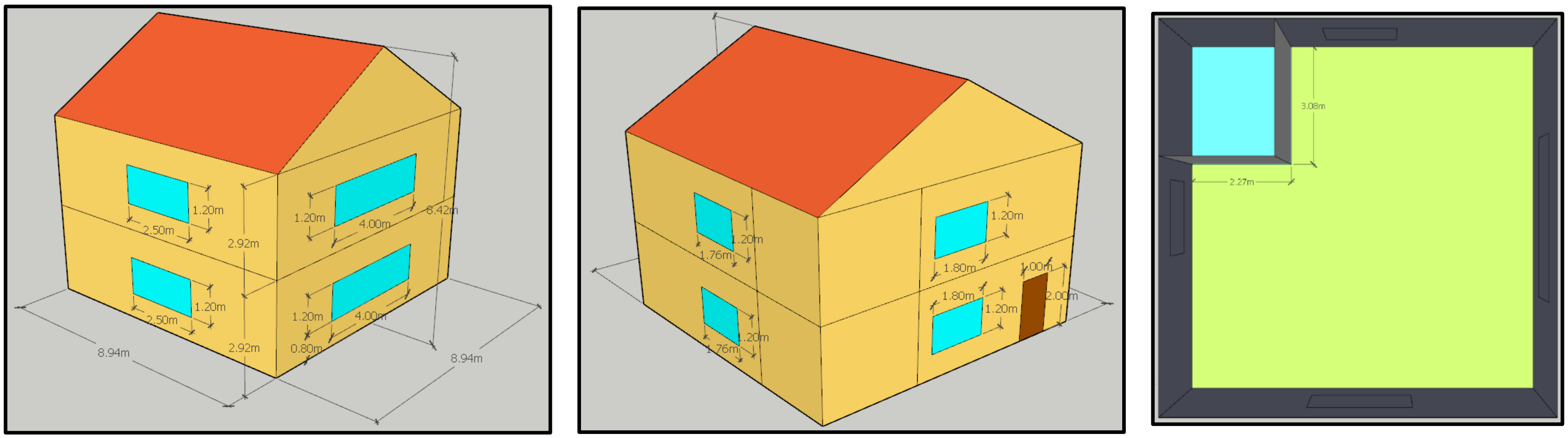
B



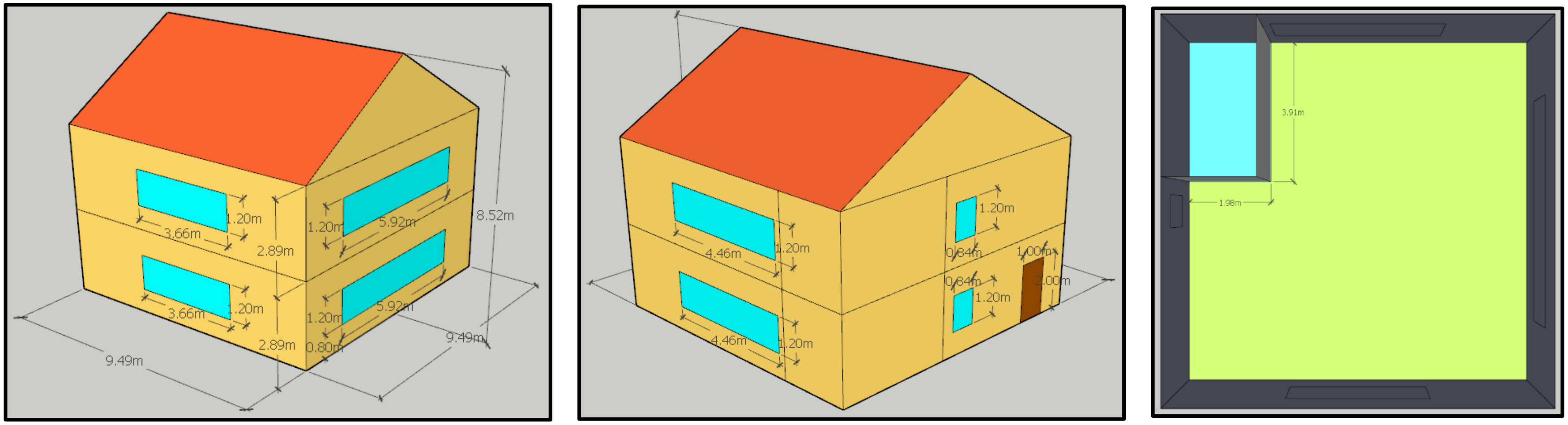
C


1.20m
2.38m
1.20m
2.38m
2.46m
1.20m
3.84m
7.45m
1.20m
3.84m
0.80m
2.40m
8.77m
8.77m
2.88m
1.20m
2.88m
1.20m
1.20m
0.54m
1.00m
2.00m
1.20m
0.54m
3.50m
1.92m

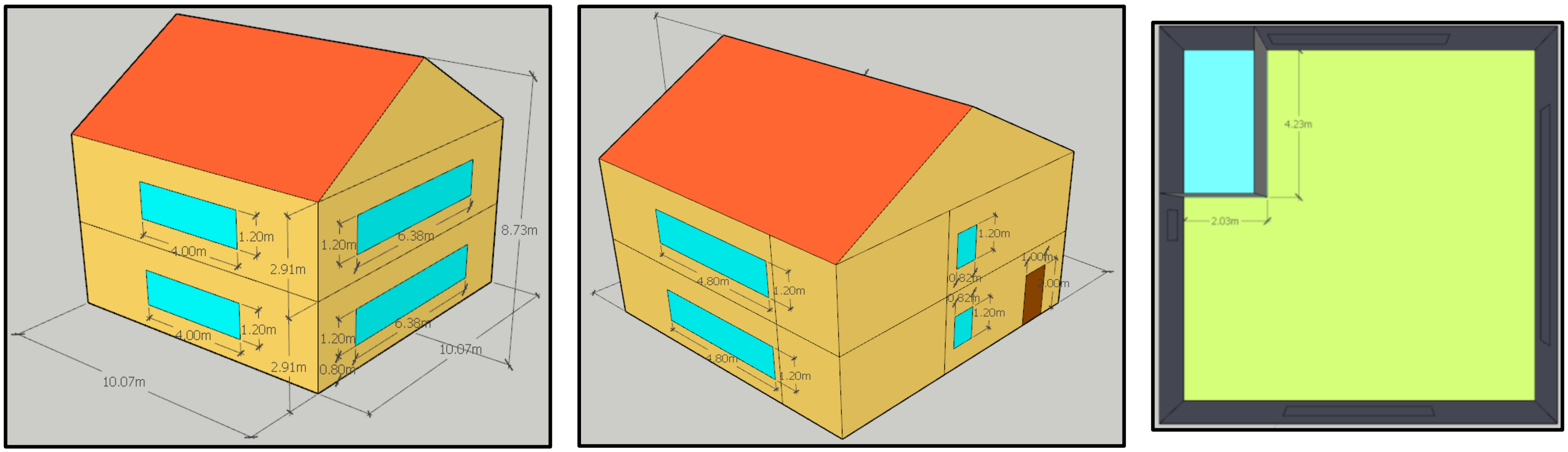
D


1.20m
2.50m
2.92m
1.20m
4.00m
8.42m
1.20m
2.50m
1.20m
4.00m
2.92m
0.80m
8.94m
8.94m
1.20m
1.76m
1.20m
1.76m
1.20m
1.80m
1.00m
1.80m
1.20m
2.00m
3.08m
2.27m

E


1.20m
3.66m
2.89m
1.20m
5.92m
8.52m
3.66m
1.20m
2.89m
1.20m
0.80m
5.92m
9.49m
9.49m
4.46m
1.20m
4.46m
1.20m
1.20m
0.84m
1.00m
0.84m
1.20m
3.91m
1.98m

F


1.20m
4.00m
2.91m
1.20m
6.38m
8.73m
4.00m
1.20m
2.91m
1.20m
0.80m
6.38m
10.07m
10.07m
4.80m
1.20m
4.80m
1.20m
1.20m
0.82m
1.00m
0.82m
1.20m
4.23m
2.03m

G

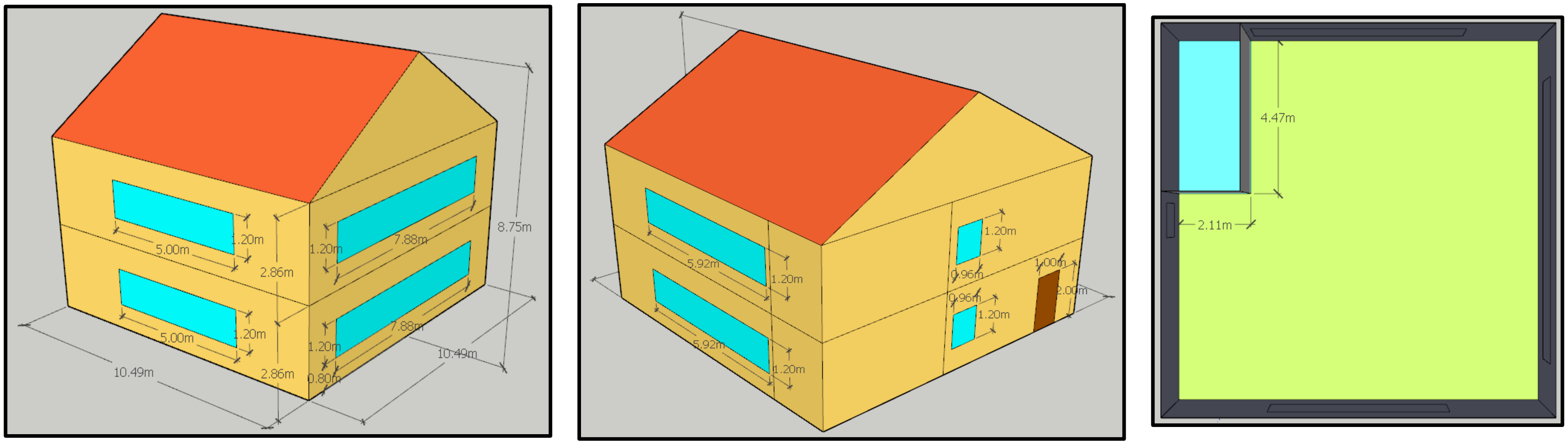


Figure A.1. *Gemetry overview of the analysed buildings defined using the Energy Plus software – left column: South and West view, middle column: North and East view, right column: floor plan (living area in green and restroom in blue); where:* ***A*** *– RSFH_1;* ***B*** *– RSFH_2;* ***C*** *– RSFH_3;* ***D*** *– RSFH_4;* ***E*** *– RSFH_5;* ***F*** *– RSFH_6;* ***G*** *– RSFH_7*

APPENDIX 4 – HVAC SYSTEMS SCHEMAS OF THE ANALYSED BUILDINGS

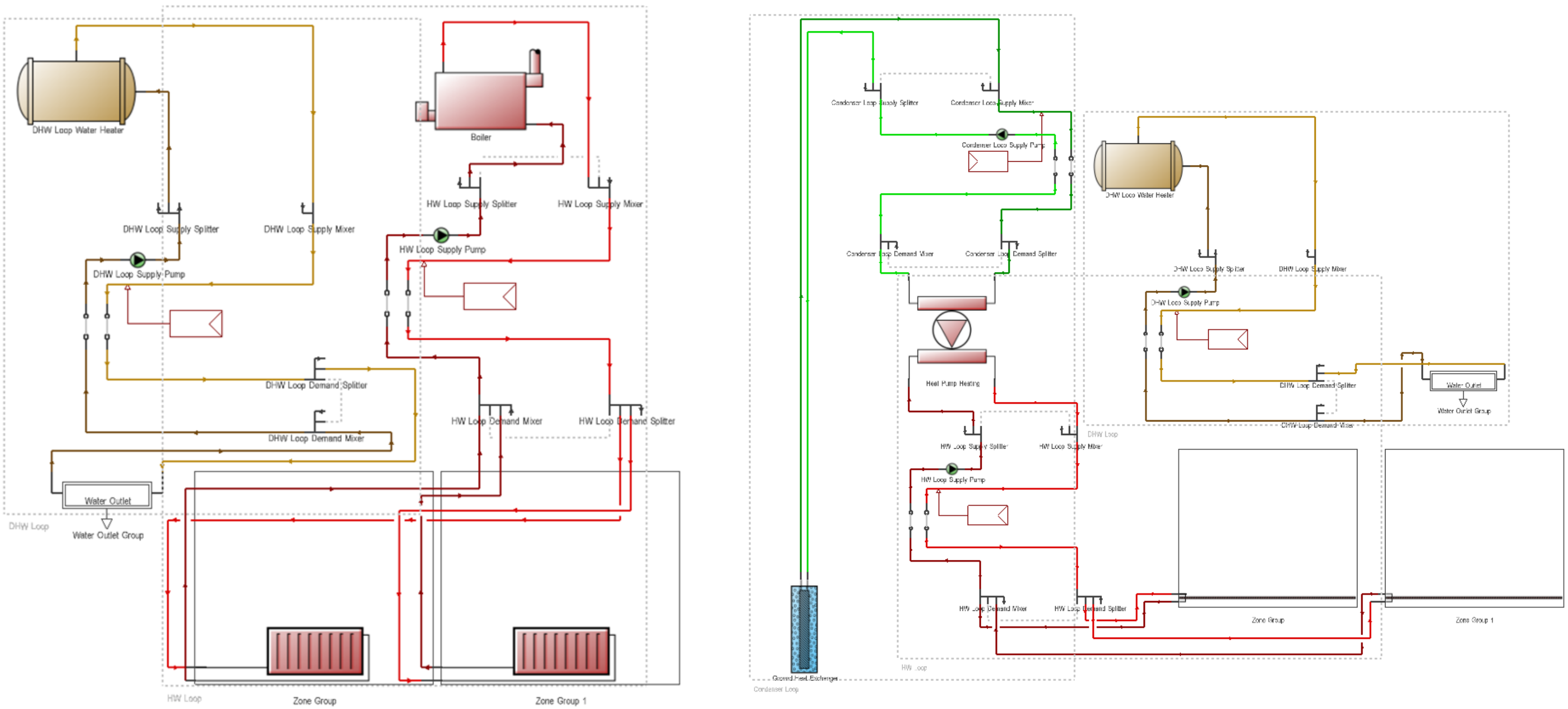
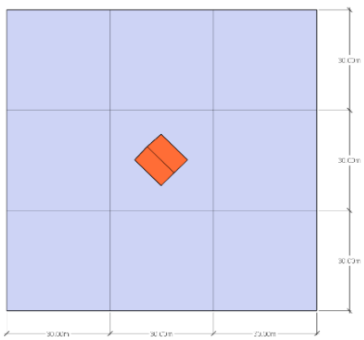
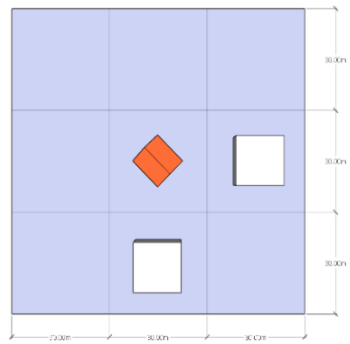
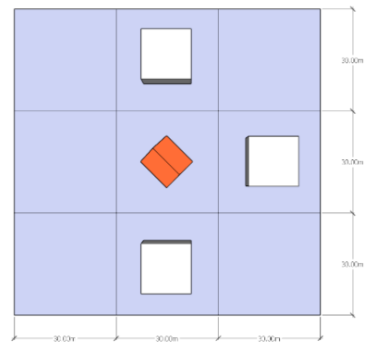


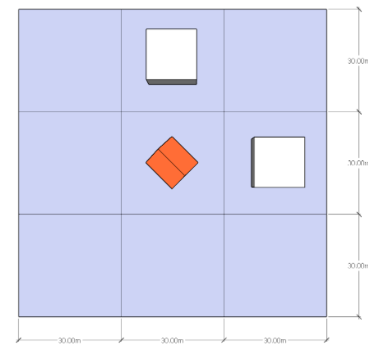
Figure A.2. *The defined installations schemas in the Energy Plus software; traditional system with heating stove (left) and ones with application of GHP (right)*

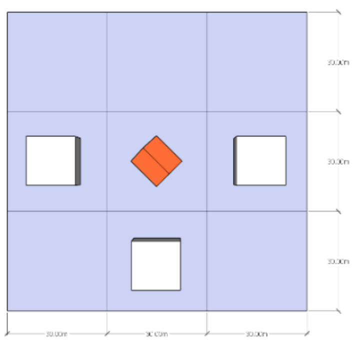
APPENDIX 5 – BUILDINGS CLOSEST SURROUNDING VARIANTS

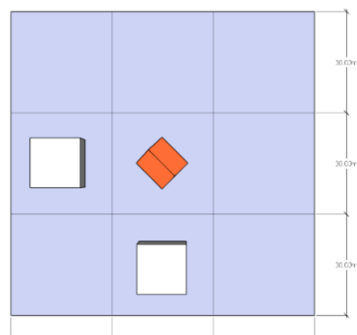

SV_0

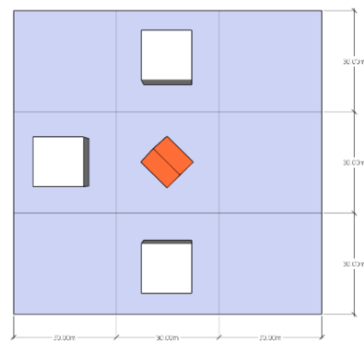

SV_1

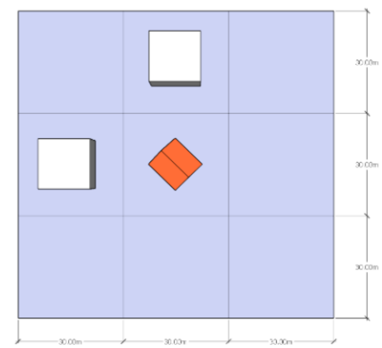

SV_2


SV_3


SV_4


SV_5


SV_6


SV_7

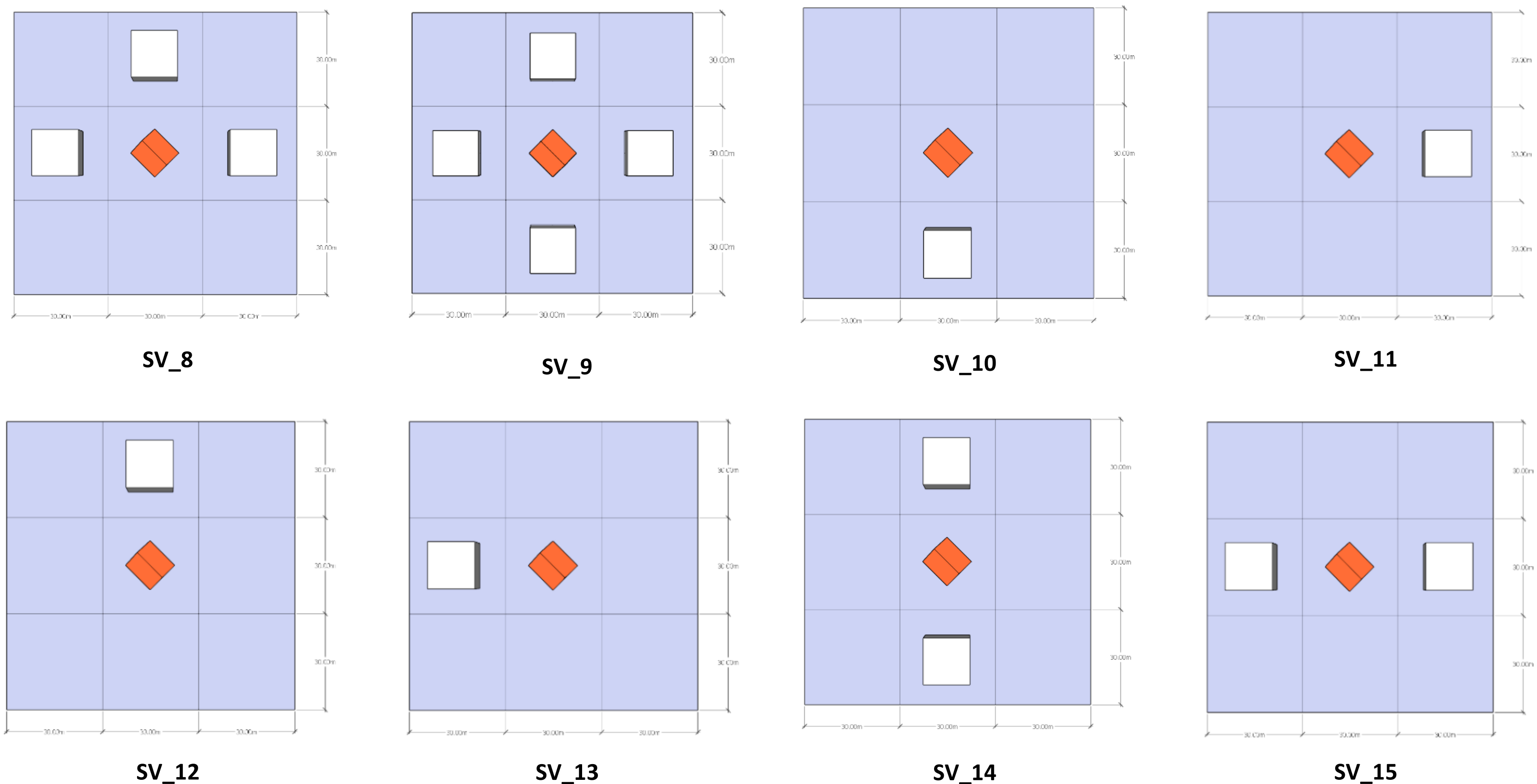


Figure A.3. *Schemas of the analysed closest surrounding variants applied into the TEAC software*

APPENDIX 6 – SCRIPT OF THE DEFINED NN USED FOR HEATING DEMAND PREDICTION PURPOSES

In this appendix, a script with a neural network, which was obtained by means of *Matlab* software, is shown. The below-presented code is valid for the network used for hourly heating demand predictions, nevertheless remaining two networks (used for predictions of monthly and daily heating consumptions) look similar, with the only change of input and output data (lines [6] and [7] of the code). Once the network is trained, it can be called using proper input data, *e.g. net(new_input_data)*; as a result, we obtain heating energy-related predictions. In the below-presented code, comments are presented in green, preceded with the % symbol.

```
[1] % Solve an Input-Output Fitting problem with a Neural Network
[2] % Script generated by Neural Fitting app
[3] % This script assumes these variables are defined:
[4] % input_H - input data
[5] % output_H - target data
[6]     x = input_H';
[7]     t = output_H';
[8] % Choose a Training Function
[9]     trainFcn = 'trainlm';   % Levenberg-Marquardt backpropagation
[10] % Create a Fitting Network
[11]    hiddenLayerSize = 12;
[12]    net = fitnet(hiddenLayerSize,trainFcn);
[13] % Choose Input and Output Pre/Post-Processing Functions
[14]    net.input.processFcns = {'removeconstantrows','mapminmax'};
[15]    net.output.processFcns = {'removeconstantrows','mapminmax'};
[16] % Setup Division of Data for Training, Validation, Testing
[17]    net.divideFcn = 'dividerand';   % Divide data randomly
[18]    net.divideMode = 'sample';      % Divide up every sample
[19]    net.divideParam.trainRatio = 70/100;
[20]    net.divideParam.valRatio = 15/100;
[21]    net.divideParam.testRatio = 15/100;
[22] % Choose a Performance Function
[23]    net.performFcn = 'mse';         % Mean Squared Error
[24] % Choose Plot Functions
[25]    net.plotFcns = {'plotperform','plottrainstate','ploterrhist', 'plotregression', 'plotfit'};
[26] % Train the Network
[27]    [net,tr] = train(net,x,t);
[28] % Test the Network
[29]    y = net(x);
[30]    e = gsubtract(t,y);
[31]    performance = perform(net,t,y)
[32] % Recalculate Training, Validation and Test Performance
```

```
    trainTargets = t .* tr.trainMask{1};
    valTargets = t .* tr.valMask{1};
    testTargets = t .* tr.testMask{1};
    trainPerformance = perform(net,trainTargets,y)
    valPerformance = perform(net,valTargets,y)
    testPerformance = perform(net,testTargets,y)
% View the Network
    view(net)
% Plots
%figure, plotperform(tr)
%figure, plottrainstate(tr)
%figure, ploterrhist(e)
%figure, plotregression(t,y)
%figure, plotfit(net,x,t)
% Deployment
    if (false)
% Generate MATLAB function for neural network for application
% deployment in MATLAB scripts or with MATLAB Compiler and Builder
% tools, or simply to examine the calculations your trained neural
% network performs
        genFunction(net,'myNeuralNetworkFunction');
        y = myNeuralNetworkFunction(x);
    end
    if (false)
% Generate a matrix-only MATLAB function for neural network code
% generation with MATLAB Coder tools
        genFunction(net,'myNeuralNetworkFunction','MatrixOnly','yes');
        y = myNeuralNetworkFunction(x);
    end
    if (false)
% Generate a Simulink diagram for simulation or deployment with
% Simulink Coder tools.
        gensim(net);
    end
```

APPENDIX 7 – SOME MANUALS ON HOW TO USE THE *TEAC* SOFTWARE

This section presents some manuals on how to define a residential area using the *TEAC* software. In this segment, the approach which was used for the definition of examples presented in section **3.8** is shown. Additionally, this chapter contains some syntaxes, used by the code of the *TEAC* software.

A.7.1. MANUALS FOR EXAMPLE NO. 1

Example no. 1. is presented in subsection **3.8.1**. The definition process starts in the first module (see more in subsection **3.7.1**) of the *TEAC* software in order, as follows:

- definition of the analysed area size, expressed by the number of parcels, horizontally (X_A) and vertically (Y_A):

{X_A, Y_A}

- selection of the built environment type out of available ones in the *TEAC* software (see more in subsection **3.7.1**):

{X_A, Y_A, *built environment type*}

In this case, the area is 2x2 parcels, defined using a manual selection (**DT1**). The input syntax is as follows:

{2, 2, *DT1*}

The next step is to define an assignment of buildings (using their type), as well as their' orientations (see more in subsection **3.7.1**). Because the **DT1** method is used, each building is defined separately and manually, using the following outline:

{X_i_Y_i, *building type*, *building orientation*}

Thus, the analysed case is defined as follows:

{*1_1*, 1, 6};

{*2_1*, 3, 7};

{*1_2*, 7, 0};

{*2_2*, 5, 3}

The graphical interpretation of the above-mentioned procedure is shown in **Figure A.4**. The buildings assignment is shown in parts (**A**) and (**B**) – the both methods are available and they can be used interchangeably in the *TEAC* software. Part (**C**) shows buildings orientation, while part (**D**) presents the closest surrounding variant (see **Appendix 6**) – it is selected automatically, after area definition, based on buildings placement.

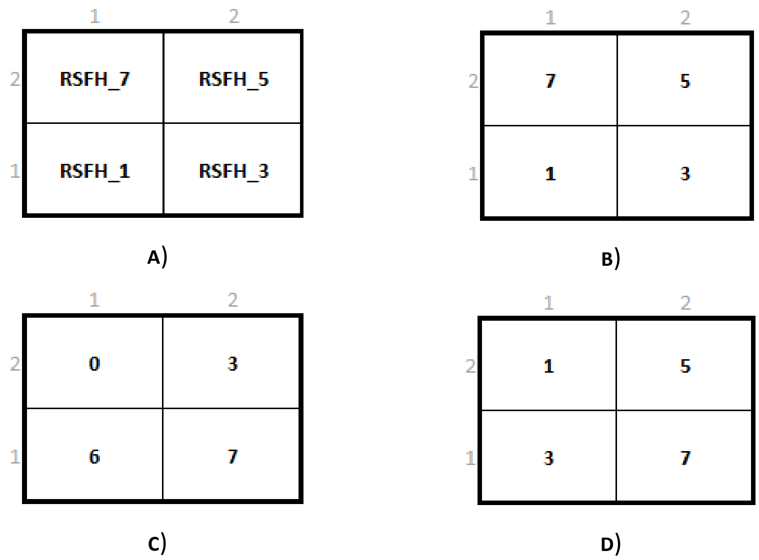


Figure A.4. *Description of the analysed area for example no. 1: A) building types, B) numbers of building types, C) orientation variants, D) surrounding variants*

Below, the summary of the defined area is shown, as follows:

- object ***1_1***: RSFH_1, rotated by 270 degrees (variant no. 6), with 3rd surrounding variant,
- object ***2_1***: RSFH_3, rotated by 315 degrees (variant no. 7), with 7th surrounding variant,
- object ***1_2***: RSFH_7, with base orientation (variant no. 0), with 1st surrounding variant,
- object ***2_2***: RSFH_5, rotated by 135 degrees (variant no. 3), with 5th surrounding variant.

The schema of how each of the building is defined in the *TEAC* software is as follows:

{X_i_Y_i, *building type*, *building orientation*, *closest surrounding variant*}

According to the above information, the analysed area (example no. 1) is defined as shown below:

{1_1, RSFH_1, 6, 3} or {1_1, 1, 6, 3};

{2_1, RSFH_3, 7, 7} or {2_1, 3, 7, 7};

{1_2, RSFH_7, 0, 1} or {1_2, 7, 0, 1};

{2_2, RSFH_5, 3, 5} or {2_2, 5, 3, 5}

The next step is to define the input data for NN analyses in module 2 of the programme. The schema of the NN input data is as follows:

{*analysis type*, *localization*, X_i_Y_i, *building enclosure variant*, *heating system variant*}

In this example, the 2nd module is used twice, for the hourly heating demand predictions for the base and modernized scenarios. Based on the input data, the *TEAC* software generates some csv-type files; in this case, the both input and output files have 8760 rows (hourly distributed predictions) for each combination. The input files have 14 columns, while the output files have just one (heating demand). For the analysed area the following inputs were used (base scenario on left and modernized on right).

{H, *Lodz*, 1_1, *base*, *base*} and {H, *Lodz*, 1_1, 2, 0.87};

{H, *Lodz*, 2_1, *base*, *base*} and {H, *Lodz*, 2_1, 2, 0.87};

{H, *Lodz*, 1_2, *base*, *base*} and {H, *Lodz*, 1_2, 2, 0.87};

{H, *Lodz*, 2_2, *base*, *base*} and {H, *Lodz*, 2_2, 2, 0.87}

Moving forward, results are generated in the 3rd module of the *TEAC* software. As the default results, maps of heating and electricity consumptions as well as CO_2 emissions are generated. The form in which those maps are received out of the programme is shown in **Figure A.5**; basically, each map is a csv-type file with values for the considered scenario. The received values are always express with two sets of outputs: total annual sums and rates per occupied area for each building (below the total amounts are presented).

	1	2
2	10 543.69	13 973.10
1	28 111.44	23 376.18

A)

	1	2
2	6 260.39	5 323.26
1	2 348.56	2 712.54

B)

	1	2
2	18 813.03	15 636.62
1	7 717.76	13 653.05

C)

	1	2
2	12 886.15	10 676.08
1	5 297.52	9 287.03

D)

	1	2
2	8 323.84	8 381.92
1	10 900.13	11 126.19

E)

	1	2
2	5 431.35	4 538.20
1	2 169.60	3 408.91

F)

Figure A.5. *Maps with default results (example no. 1), accordingly: heating consumption for:* **A)** *base and* **B)** *modernized scenario; electricity consumption for:* **C)** *base and* **D)** *modernized scenario;* CO_2 *emissions for:* **E)** *base and* **F)** *modernized scenario*

Using the 3rd module of the *TEAC* software it is possible to obtain some supplementary results of the analysed BC. The examined scenario includes the usage of solar energy. The schema of the input used for the solar energy examination is shown below.

{*building selection*, L_{PV}, B_{PV}, η_{PV}}

Thus, in this case, it looks as follows:

{*all*, *standard*, *standard*, *standard*}

The above-introduced procedure might be performed manually, for each building out of the analysed area; therefore, the used input looks as follows:

{1_1, 1.65, 1.00, 0.1885};
{2_1, 1.65, 1.00, 0.1885};
{1_2, 1.65, 1.00, 0.1885};
{2_2, 1.65, 1.00, 0.1885}

Whenever a solar energy analysis is performed, annual electricity production for all the selected buildings is obtained as the main output (calculations are performed with hourly steps). Those outputs might be furtherly used for *e.g.* generating the solar energy maps, as shown in **Figure A.6**.

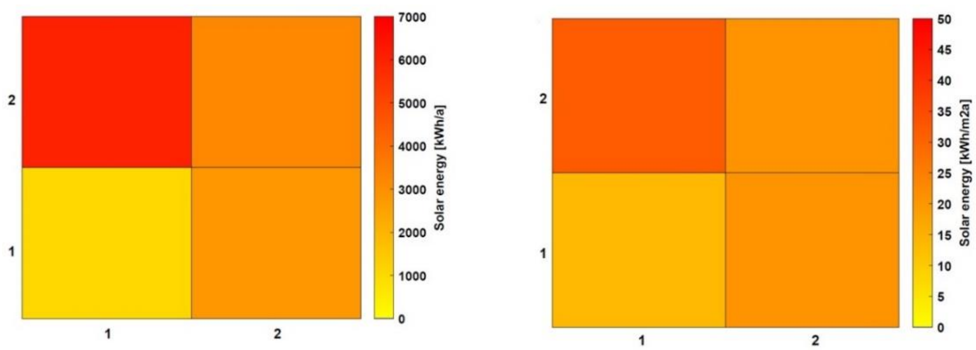


Figure A.6. *Map of the solar energy potential (example no.1): annual total production (on left) and per unit of occupied area (on right)*

The economic analysis is very simple to define – it is performed with an input, including building selection and the preferred method. The input for the economic analysis has a structure as follows:

{*building selection*, SPBT, NPV, LCC}

An exemplary input (valid for this case) looks like below.

{*all*, 1, 1, 1}

It might be performed fully manually, for each of the building out of the analysed area:

{1_1, 1, 1, 1};

{2_1, 1, 1, 1};

{1_2, 1, 1, 1};

{2_2, 1, 1, 1}

There are several types of available results obtained from the economic analysis (see more in subsection **3.7.6**). Using the SPBT method, a single value is obtained for each building, while for the two remaining methods (NPV and LCC), a time-distribution of financial profits are calculated. Additionally, for those methods, the repayment time is also estimated (expressed with the NPV_0 and LCC_0 indicators). Those time-distributed financial outputs are shown in subsection **3.7.6**, in **Figure 3.31** (NPV method) and **Figure 3.32** (LCC method), while maps with economic indexes are shown below, in **Figure A.7**.

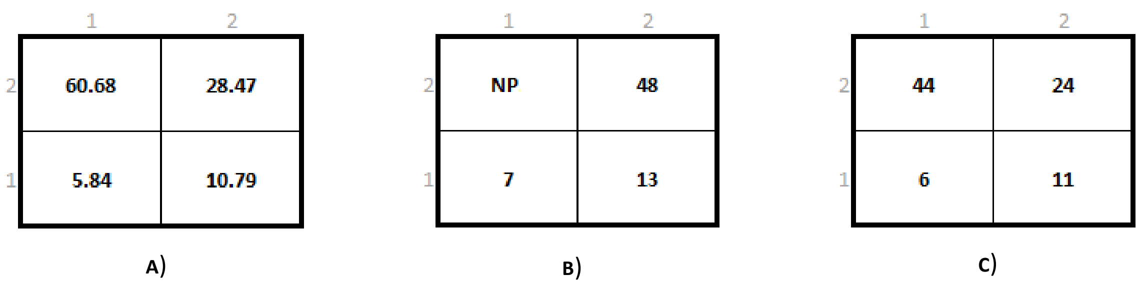


Figure A.7. *The economic indexes for the **V2** variant, accordingly A) SPBT, B) NPV_0, C) LCC_0*

The last type of outputs available in the *TEAC* software relates to the environmental impacts of the proposed modernizations. The calculations are made based on heating and electricity consumptions for each building out of the analysed area. Those considerations are performed using the environmental submodule of the programme (see more in subsection **3.7.7**). The calculation choice is very simple – a selection is required. The input for the environmental analysis is rather simple, it based on the selection of gasses, which emissions should be calculated; it has a structure as follows:

{*building selection*, CO_2, SO_2, NO_x, $PM_{2.5}$, PM_{10}}

For the analysed area the used input looks like below.

{*all*, 1, 1, 1, 1, 1}

Or it might be defined for each building manually:

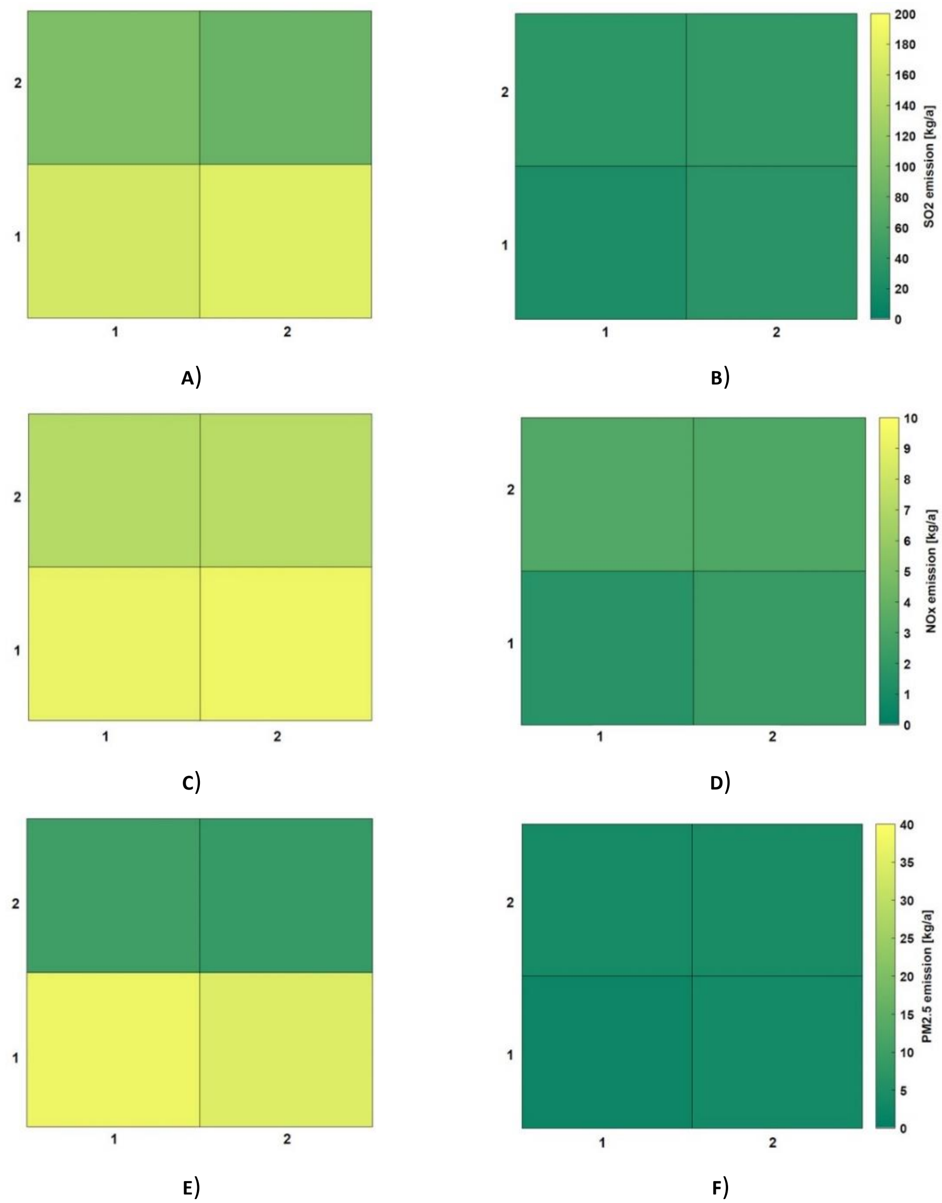
{1_1, 1, 1, 1, 1, 1};

{2_1, 1, 1, 1, 1, 1};

{1_2, 1, 1, 1, 1, 1};

{2_2, 1, 1, 1, 1, 1}

The amount of emissions can be expressed using an annual sum or amount per unit of the occupied area. Again, all the obtained results are gathered in csv-type files. Those values can be furtherly used to define emission maps, for all considered scenarios. Some emission results, presented using maps are shown in **Figure A.8** (without CO_2, emissions, which are already shown in **Figure A.5**). Some additional environmental-based outputs for the considered case are shown in subsection **3.8.1**.



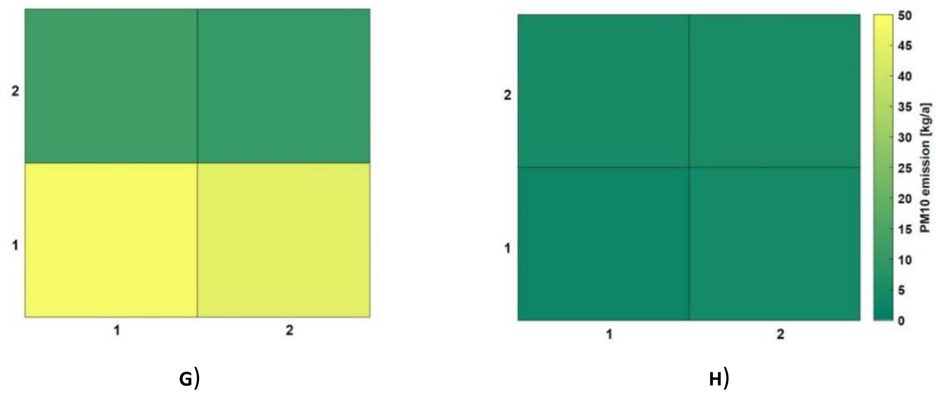


Figure A.8. *Maps of different GHG emissions for the analysed area (example no. 1), accordingly:* ***A****) SO_2 before and* ***B****) after modernization;* ***C****) NO_x before and* ***D****) after modernization;* ***E****) $PM_{2.5}$ before and* ***F****) after modernization;* ***G****) PM_{10} before and* ***H****) after modernization*

A.7.2. MANUALS FOR EXAMPLE NO. 2

This exemplary BC consists of 27 buildings and it is presented in subsection **3.8.2**. The area definition is performed in the same way as for example no. 1 (see more in section **A.7.1**). In this case, the area is 6x5 parcels, defined using a manual selection (**DT1**). The input looks as follows:

{6, 5, *DT1*}

The next step is to define the distribution of buildings and their orientations – it is performed the same way as in the previous example. In total, 30 lines are required to define the analysed area; some of them are presented below.

{1_1, RSFH_1, 6, 3} or {1_1, 1, 6, 3};

{2_1, RSFH_3, 7, 7} or {2_1, 3, 7, 7};

{3_1, 0, 0, 0} or {3_1, 0, 0, 0};

{4_1, RSFH_7, 6, 3} or {4_1, 7, 6, 3};

...

{3_5, RSFH_4, 2, 4} or {3_5, 4, 2, 4};

{4_5, RSFH_6, 3, 4} or {4_5, 6, 3, 4};

{5_5, RSFH_7, 4, 4} or {5_5, 7, 4, 4};

{6_5, RSFH_6, 0, 5} or {6_5, 6, 0, 5}

The graphical interpretation of all the information related to buildings' distribution for the analysed area is shown in **Figure A.11**.

	1	2	3	4	5	6
5	RSFH_6	RSFH_4	RSFH_4	RSFH_6	RSFH_7	RSFH_6
4	X	RSFH_1	RSFH_5	RSFH_1	RSFH_4	RSFH_4
3	RSFH_1	RSFH_7	RSFH_5	RSFH_2	RSFH_1	X
2	RSFH_7	RSFH_5	RSFH_2	RSFH_2	RSFH_1	RSFH_5
1	RSFH_1	RSFH_3	X	RSFH_7	RSFH_1	RSFH_6

A)

	1	2	3	4	5	6
5	6	4	4	6	7	6
4	X	1	5	1	4	4
3	1	7	5	2	1	X
2	7	5	2	2	1	5
1	1	3	X	7	1	6

B)

	1	2	3	4	5	6
5	0	3	2	3	4	0
4	X	7	2	1	0	7
3	1	6	0	6	4	X
2	0	3	5	5	1	7
1	6	7	X	6	4	0

C)

	1	2	3	4	5	6
5	11	4	4	4	4	5
4	X	2	9	9	9	7
3	1	9	9	9	6	X
2	2	9	8	9	9	5
1	3	7	X	3	8	7

D)

Figure A.9. *Description of the analysed area for example no. 2: A) building types, B) numbers of building types, C) orientation variants, D) surrounding variants*

Out of the buildings distribution data, some statistical information can be obtained. Some exemplary data referring to the considered built environment is shown in **Table 3.20** (see more in subsection **3.8.2**) as well as in **Table A.1**.

Table A.1. *Summarized data of buildings placement in the analysed BC (example no. 2)*

		RSFH TYPE						
		1	**2**	**3**	**4**	**5**	**6**	**7**
#		7	3	1	4	4	4	4
ORIENTATION VARIANT	0	-	-	-	1	1	3	1
	1	3	-	-	-	-	-	-
	2	-	-	-	1	1	-	-
	3	-	-	-	1	1	1	-
	4	2	-	-	-	-	-	1
	5	-	2	-	-	-	-	-
	6	1	1	-	-	-	-	2
	7	1	-	1	1	1	-	-

Example no. 2 is focused on the analysis of the impact of exterior climate condition. For the purpose of the performed study, the 2nd module of the programme is used twenty times to examined all the localizations impact for scenarios before and after buildings refurbishment (variants **V0** and **V1** described in subsection **3.8.2**). An hourly heating demands predictions are performed; thus the input (14 columns) and output (1 column) files have 8760 rows of data for each combination (27 buildings, 10 localizations and 2 modernization variants). The procedure of input file preparation is already explained in section **A.7.1**. The list of all the available localizations is presented below.

[*Gdansk*, *Leba*, *Szczecin*, *Pila*, *Wroclaw*, *Lodz*, *Warsaw*, *Bialystok*, *Cracow*, *Rzeszow*]

Some exemplary input files look as follows (base scenario on left and modernized on right):

{H, *Gdansk*, *all*, *base*, *base*} and {H, *Gdansk*, *all*, 2, 0.87};
{H, *Leba*, *all*, *base*, *base*} and {H, *Leba*, *all*, 2, 0.87};
{H, *Szczecin*, *all*, *base*, *base*} and {H, *Szczecin*, *all*, 2, 0.87};
{H, *Pila*, *all*, *base*, *base*} and {H, *Pila*, *all*, 2, 0.87};
{H, *Wroclaw*, *all*, *base*, *base*} and {H, *Wroclaw*, *all*, 2, 0.87};
{H, *Lodz*, *all*, *base*, *base*} and {H, *Lodz*, *all*, 2, 0.87};
{H, *Warsaw*, *all*, *base*, *base*} and {H, *Warsaw*, *all*, 2, 0.87};
{H, *Bialystok*, *all*, *base*, *base*} and {H, *Bialystok*, *all*, 2, 0.87};
{H, *Cracow*, *all*, *base*, *base*} and {H, *Cracow*, *all*, 2, 0.87};
{H, *Rzeszow*, *all*, *base*, *base*} and {H, *Rzeszow*, *all*, 2, 0.87}

Various results can be obtained from the 3rd module of the *TEAC* software. As the default results, we are a set of maps for heating and electricity consumptions as well as CO_2 emissions are obtained (see more in subsection **3.8.2**).

Some collation of the heating and electricity LDCs can be seen in **Figure A.10**. Out of the obtained results, it can be seen, that all proposed modernizations are profitable in terms of energy savings. The **V1** modernization lowers the heating demand by almost 77 %, while the annual heating consumption is decreased by up to 78 %. Electricity consumption can be decreased by up to 74 % (the **V3** scenario), decreasing the peak demand by 65 %.

The solar energy analysis is performed the same way as it was in the previous example (section **A.7.1**). The *TEAC* software uses information captured in already generated csv-type files, thus the solar energy examination is performed for all the considered localizations. Although there are some empty parcels, the sequence might be performed using the keyword '*all*' – it significantly simplifies the record without a risk of obtaining errors during calculations (for all empty parcels zero amount of produced electricity will be gained). For the analysed BC, the input used for solar energy analysis is as follows:

{*all*, 1.65, 1.00, 0.1885}

A) B)

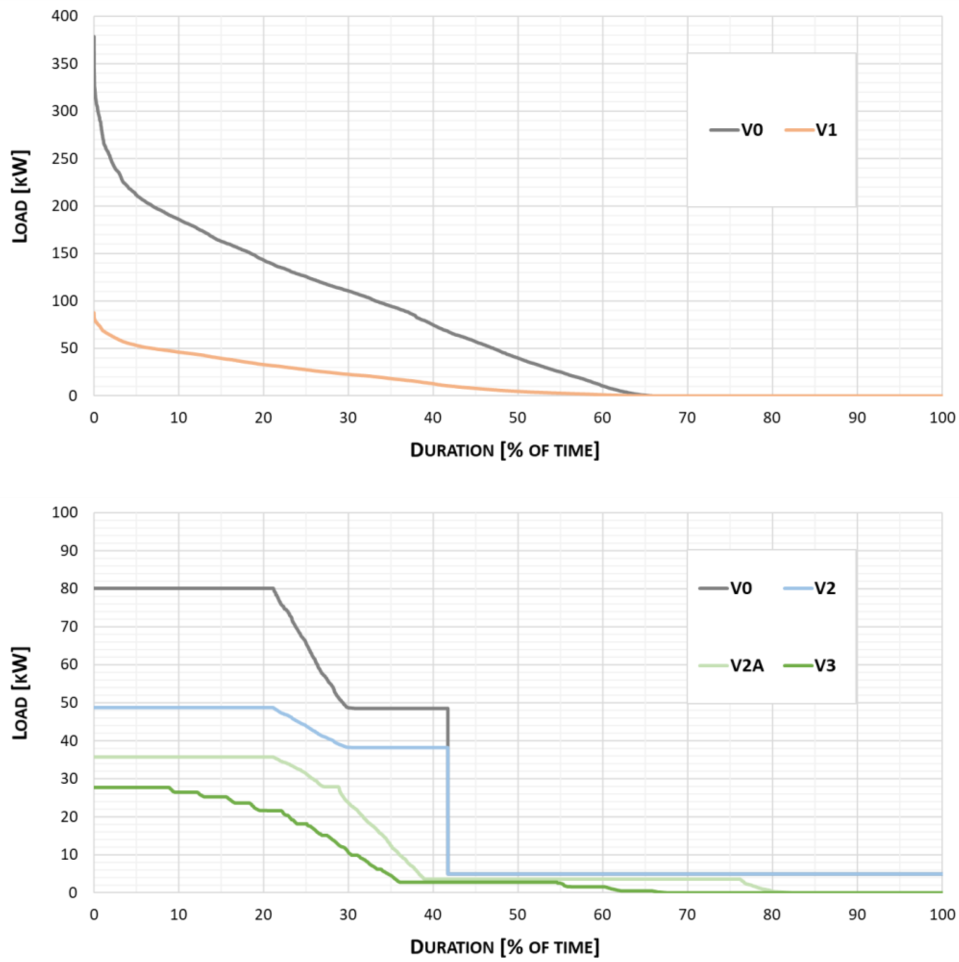


Figure A.10. *LDCs of the analysed neighbourhood – heating* ***A****) & electricity* ***B****) demands for some of the examined scenarios*

The application of wind energy is also considered in this example. Three different scenarios were studied (see more in subsection **3.8.2**), accordingly the application of the VAWT (assigned as **WE_A**) as well as the onshore (**WE_B**) and offshore (**WE_C**) HAWTs. Calculations were performed using the method introduced in subsection **3.7.5**. The wind energy submodule in the *TEAC* software requires a simple input to perform calculations. For the VAWT applications, the structure of the input looks as follows:

{*VAWT_type*, *building selection*}

The VAWT can be applied to all the buildings within the analysed area (it can be done using the keyword '*all*') or manually, using coordinates (X_i_Y_i) of the considered objects. In this example, it is performed using the keyword '*all*' – the used simplification does not affect the obtained results despite the fact of some empty parcels appearance (outputs for these parcels are equal to zero). The used input for the **WE_A** scenario looks as follows:

{VAWT_1, *all*}

For the HAWT analyses the input should be performed following the below outline:

{*HAWT_type*, *turbine number*}

Therefore, in this example inputs for the HAWT applications for onshore (**WE_B**, on left) and offshore (**WE_C**, on right) scenarios are as follows:

{HAWT_1S, 1} and {HAWT_1O, 1}

The results obtained out of the wind submodule are captured in csv-type files, as data, which can be furtherly used in numerous analyses. Same as it is done for the solar energy analysis, the wind energy examinations are performed for all the considered localizations. Moreover, the offshore wind energy calculations are performed only once and their usage is available only if one out of the seaside localizations (Gdansk, Leba, Szczecin) is considered. Thus, in this example, ten scenarios of VAWT, ten of onshore HAWT and just one offshore HAWT variants are analysed. The summarized data out of the performed analyses is presented in **Table A.2**. The system consists of 760.65 m^2 of PVs, with an efficiency of 18.85 % produced the total amount of electricity as high as 101 180.22 kWh/a (for Cracow localization), with a rating of 102.6 kWp. For wind energy, the application of 27 VAWT results in a production of 47 474.74 kWh/a electricity, in Leba localization, with maximum power at 40.5 kW. It can be seen, that in general solar energy is more profitable than wind energy for housing application in different Polish localizations. The amount of produced electricity out of solar is rather constant despite the selected localization – the values vary by up to 15 %. On the other hand, wind energy is more localization-dependent; it can be clearly seen, that some local climate conditions are more appropriate for wind turbines application. The amount of produced electricity out of the wind is as high as 84 %. It is also important to mention, that it is not recommended to use traditional meteorological data (*i.e.* TMY files) for wind energy calculations – the more accurate, locally-measured data should be used.

Out of economic considerations, the LCC analysis is performed. The procedure is the same as in the previous example. Thus, the input used in the economic submodule looks as follows:

{*all*, 0, 0, 1}

Table A.2. *Summarized data of solar and wind application for different localizations – example no. 2*

LOCALIZATION	RES	PRODUCED [kWh/a]	FINAL [kWh/a]	TOTAL [kWh/a]
GDANSK	SOLAR	89 314.24	78 329.65	98 218.36
	WIND	21 995.87	19 888.72	
LEBA	SOLAR	86 498.80	76 209.37	118 667.78
	WIND	47 474.74	42 458.41	
SZCZECIN	SOLAR	87 012.08	76 887.33	92 040.64
	WIND	16 690.02	15 153.31	
PILA	SOLAR	90 173.45	79 403.64	88 651.00
	WIND	10 223.32	9 247.36	
WROCLAW	SOLAR	97 992.23	85 818.43	95 893.77
	WIND	11 158.02	10 075.34	
LODZ	SOLAR	95 781.56	84 014.71	96 786.77
	WIND	14 157.00	12 772.06	
WARSAW	SOLAR	95 987.27	84 227.56	104 618.40
	WIND	22 560.34	20 390.84	
BIALYSTOK	SOLAR	87 731.45	77 089.41	84 103.16
	WIND	7 695.79	7 013.74	
CRACOW	SOLAR	101 180.22	88 576.76	99 012.04
	WIND	11 647.90	10 435.28	
RZESZOW	SOLAR	100 672.01	88 157.26	100 690.13
	WIND	13 807.59	12 532.87	

Where: **FINAL** – a sum of electricity used directly and received back from the grid; **TOTAL** – a sum of the **FINAL** electricity out of solar and wind

Based on the above-presented sequence, it can be seen that SPBT and NPV methods are not considered in this study. Moreover, once again the keyword ‘*all*’ is used – for all the empty parcels zero is obtained.

The last type of performed analysis relates to the environmental issues, expressed by means of GHG emissions. The procedure is already presented in the previous example. In this case, the used sequence is as follows:

{*all*, 1, 0, 0, 0, 0}

For the analysed BC, only CO_2 emissions are considered, for all buildings consisting of the examined area.

APPENDIX 8 – SUPPLEMENTARY RESULTS OBTAINED USING THE *TEAC* SOFTWARE

This section includes a presentation of some supplementary results obtained during the examined BCs analyses. All gathered results were obtained using the *TEAC* software.

A.8.1. BUILDING CLUSTER NO. 1

In this section, additionally results for the BC no. 1 are shown. A detailed description of the performed analysis, as well as the list of examined variants, can be found in section **4.1**. The base heating and electricity demands maps (the **V0** variant) are shown in **Figure A.11**. The set of heating demand maps for variants **V1**, **V3**, **V4** and **V6** can be seen in **Figure A.12**. Additionally, some electricity demand maps are shown in **Figure A.13**, for **V7** and **V9** variants. Moreover, some economic analysis is performed by means of the LCC method. Furthermore, GHG emissions for all considered variants are compared in **Table A.3**. The presented emissions show the impact of heating and electricity separately, in order to compare each modernization with the base scenario. The emissions reduction from heating demand (based on the selected scenario) starts from around 74 % (CO_2 in **V1** scenario) and can reach up to 97 % (PM_{10} in **V6** variant). Lighting system upgrade and PVs application provide major environmental protection by a reduction of GHG emission by approx. 61 % (**V9** scenario).

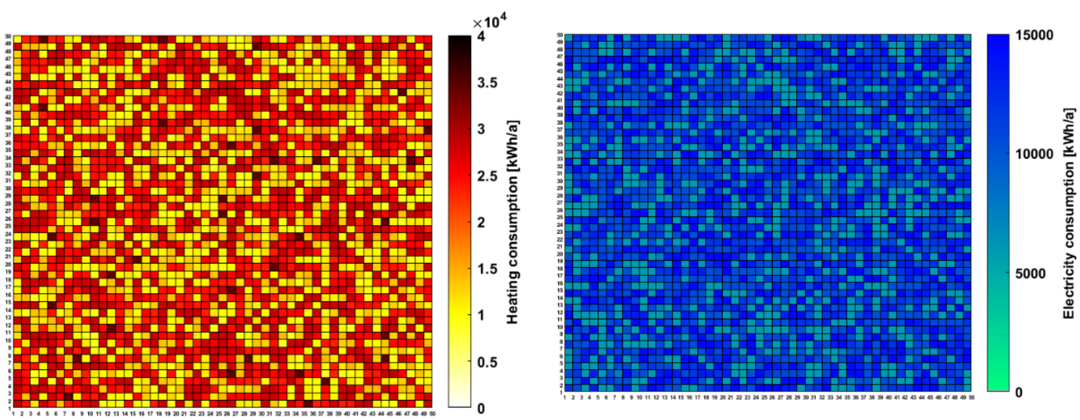


Figure A.11. *Heating (left) and electricity (right) consumptions maps for a base variant (**V0**) for the BC no. 1*

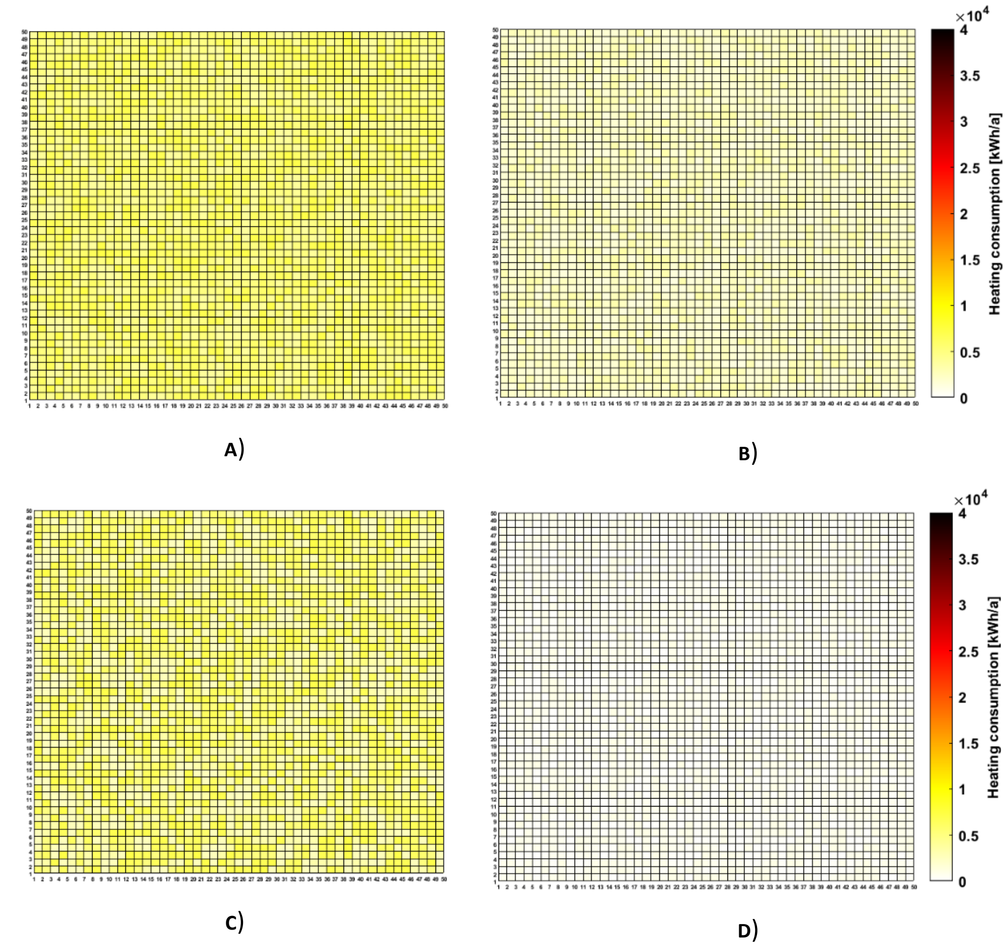


Figure A.12. *Heating consumptions maps for different scenarios for the BC no. 1, accordingly variants:* A) ***V1***; B) ***V3***; C) ***V4***; D) ***V6***

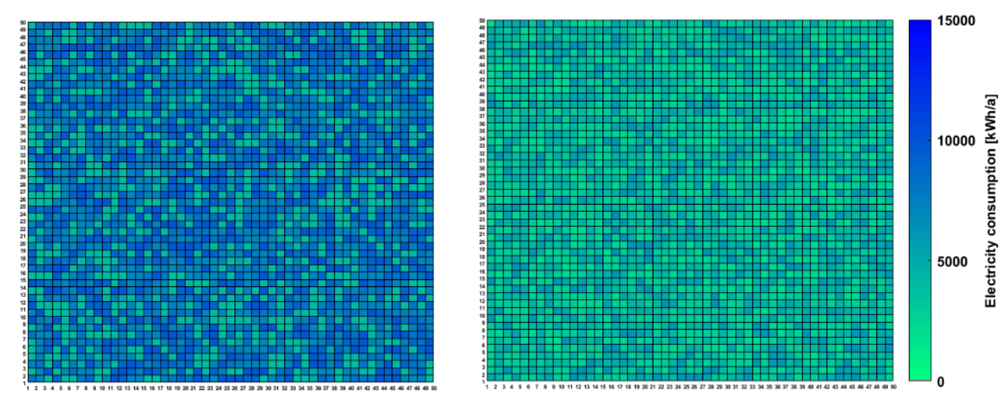


Figure A.13. *Electricity consumptions maps for the **V7** (left) and **V9** (right) scenarios for the BC no. 1*

Table A.3. *GHG emissions for the BC no. 1 – a comparison of all analysed scenarios*

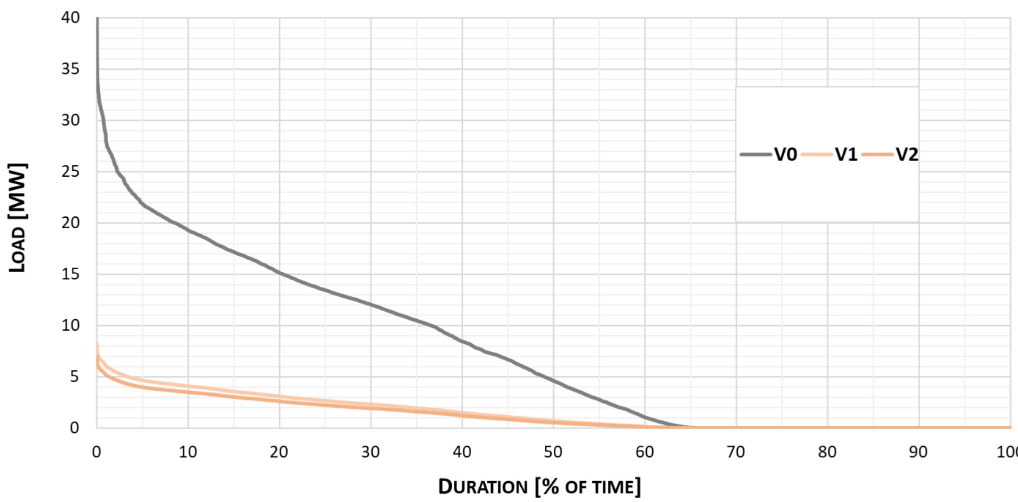
VARIANT	CO_2 [t/a]	SO_2 [t/a]	NO_x [t/a]	$PM_{2.5}$ [t/a]	PM_{10} [t/a]
$V0_H$	14 839.62	129.83	12.76	35.82	46.06
$V0_E$	7 383.17	134.90	6.19	12.77	16.48
V1	3 917.10	21.25	3.41	6.12	7.79
V2	3 397.90	17.85	2.96	5.16	6.57
V3	1 640.80	8.25	1.43	2.40	3.05
V4	3 348.37	0.06	2.98	0.60	0.60
V5	1 084.78	19.82	0.91	1.88	2.42
V6	448.30	8.19	0.38	0.78	1.00
V7	5 068.81	92.61	4.25	8.77	11.32
V8	4 084.07	74.62	3.43	7.06	9.12
V9	2 901.88	53.02	2.43	5.02	6.48

Where: **$V0_H$** – emissions out of heating energy demand for **V0**; **$V0_E$** – emissions out of electricity consumption for **V0**

A.8.2. BUILDING CLUSTER NO. 2

In this section, some additionally results for the BC no. 2 are shown. A detailed description of the performed analysis, as well as the list of examined variants, can be found in section **4.2**. A set of heating and electricity LDCs for both examined localizations are shown in **Figure A.14** and **Figure A.15**. Additionally, maps of heating and electricity demands, as well as CO_2 emission are shown in **Figure A.16**. The above-mentioned maps are presented as a comparison between the base scenario (**V0**) with one preselected variant. Moreover, some economic outputs are shown – NPV analyses (for each building type separately), in both examined localizations, can be seen in **Figure A.17** and **Figure A.18**.

A)



B)

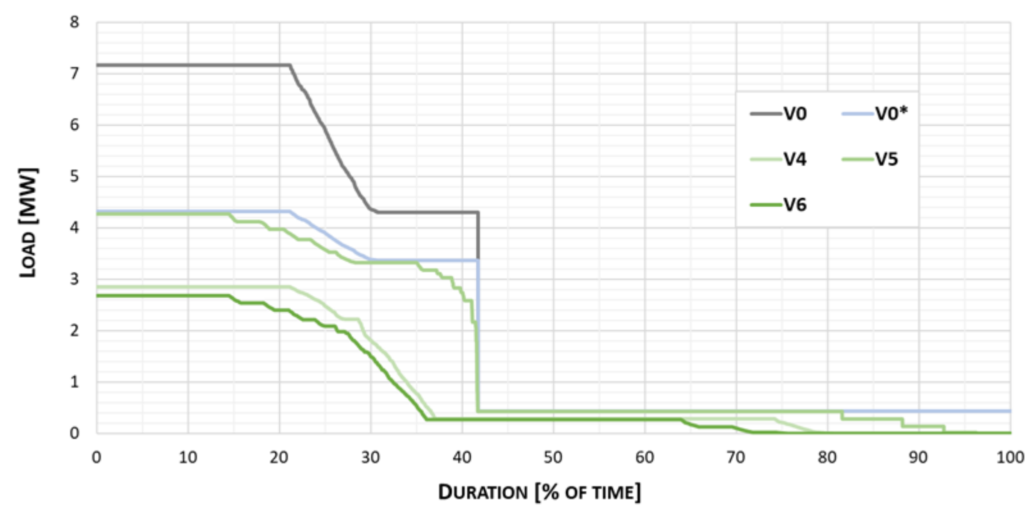
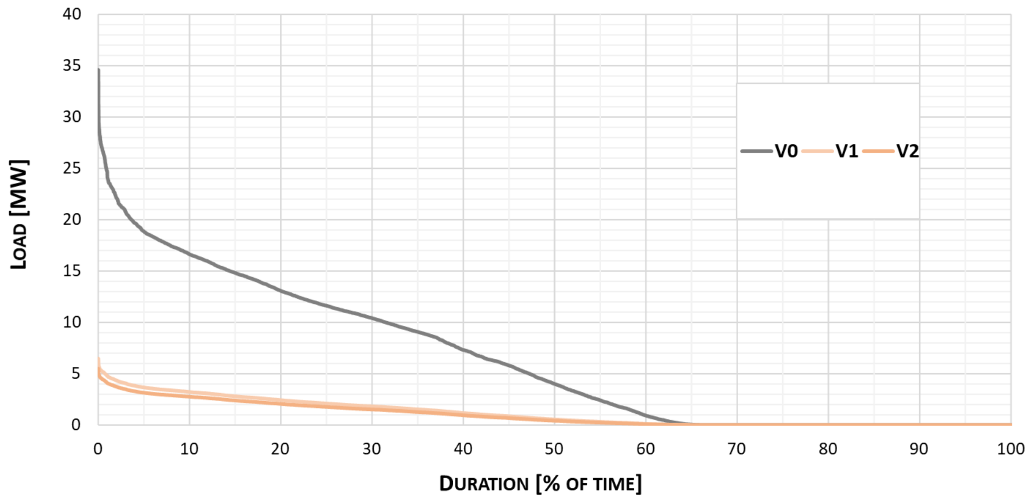


Figure A.14. *LDCs for the BC no. 2 located in Rzeszow, accordingly:* A) *heating and* B) *electricity*

A)



B)

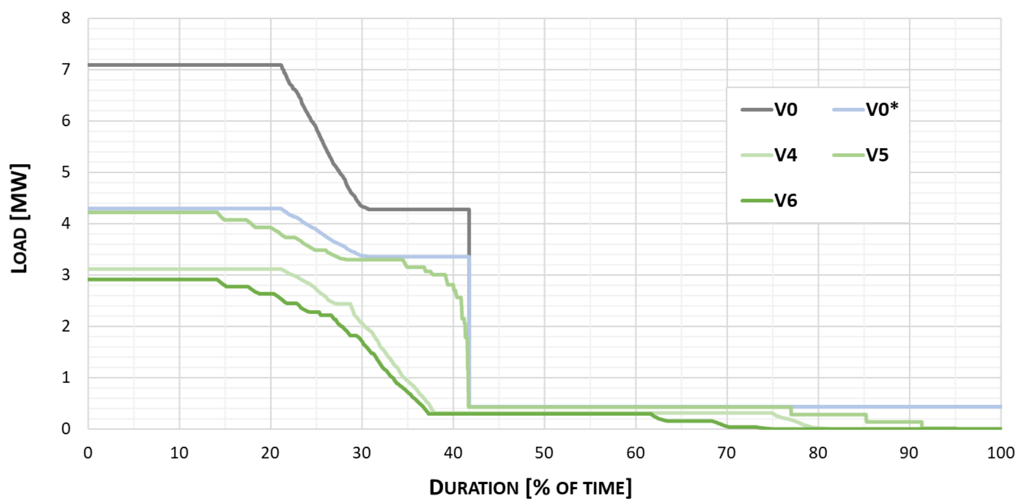
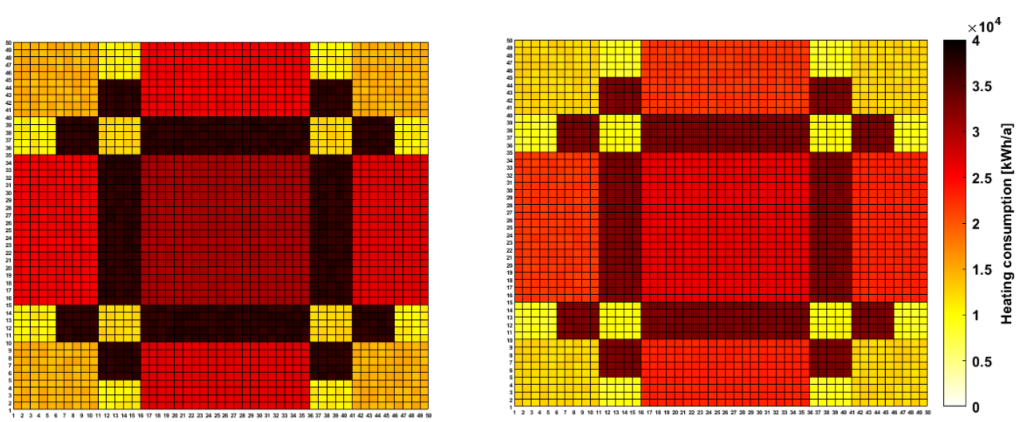


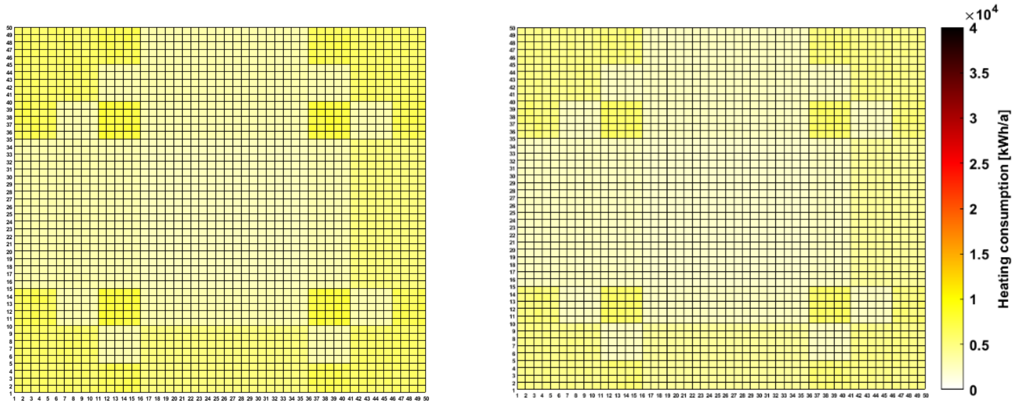
Figure A.15. *LDCs for the BC no. 2 located in Szczecin, accordingly:* **A**) *heating and* **B**) *electricity*

RZESZOW **SZCZECIN**

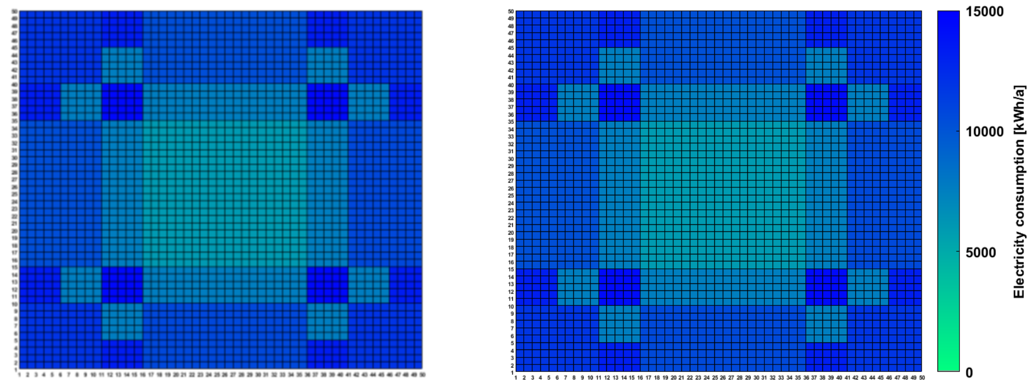
A)



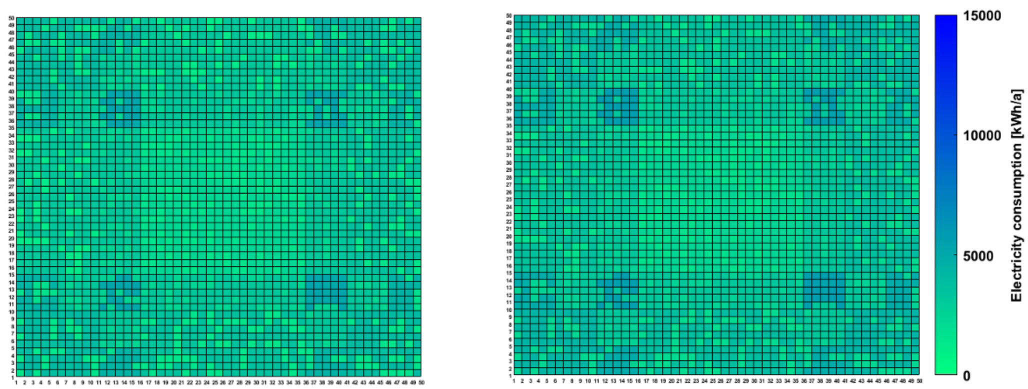
B)


×10^4
4
3.5
3
2.5
2
1.5
1
0.5
0
Heating consumption [kWh/a]

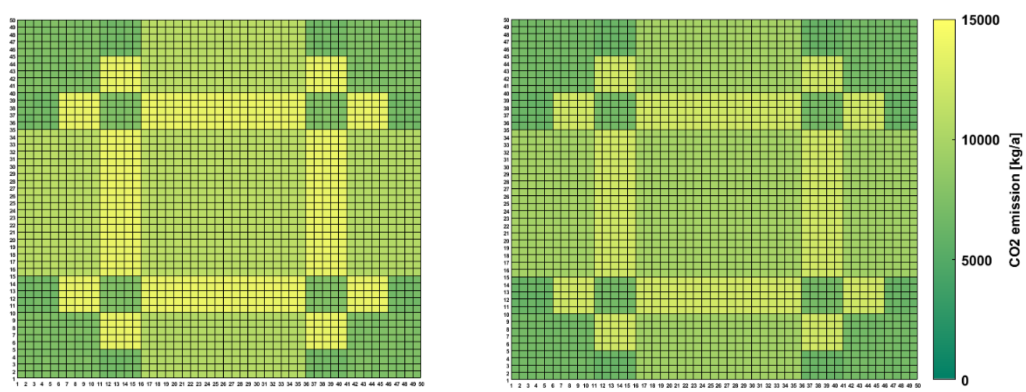
C)


15000
10000
5000
0
Electricity consumption [kWh/a]

D)


15000
10000
5000
0
Electricity consumption [kWh/a]

E)


15000
10000
5000
0
CO2 emission [kg/a]

F)

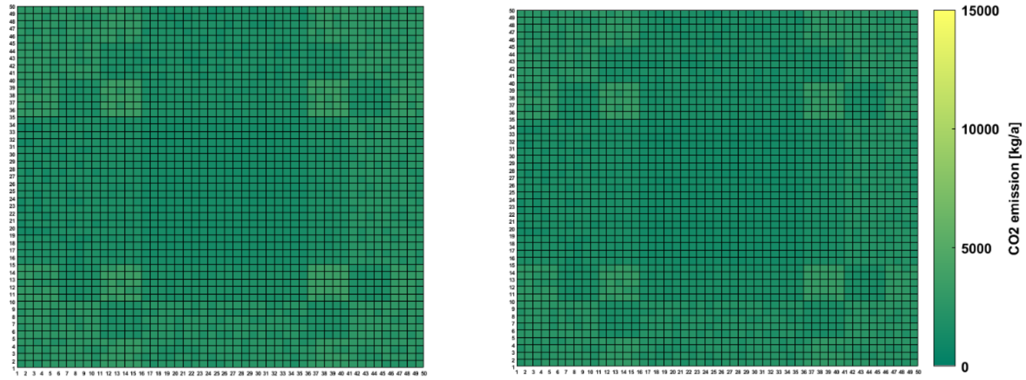


Figure A.16. *Mapping of the BC no. 2 for the both considered localizations, accordingly: **A**) heating consumption for the **V0** scenario, **B**) heating consumption for the **V2** scenario, **C**) electricity consumption for the **V0** scenario, **D**) electricity consumption for the **V6** scenario, **E**) CO_2 emissions for the **V0** scenario and **F**) CO_2 emissions for the **V6** scenario*

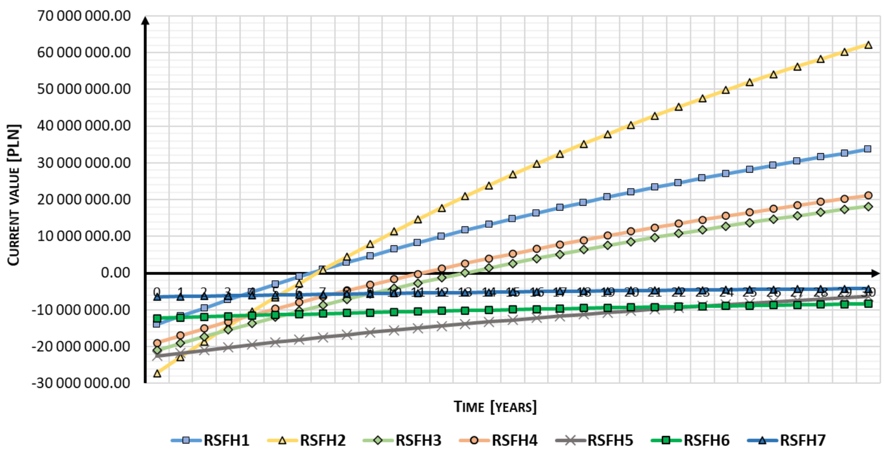


Figure A.17. *NPV analyses of the **V2** scenario for all building types in the analysed BC no. 2 located in Rzeszow*

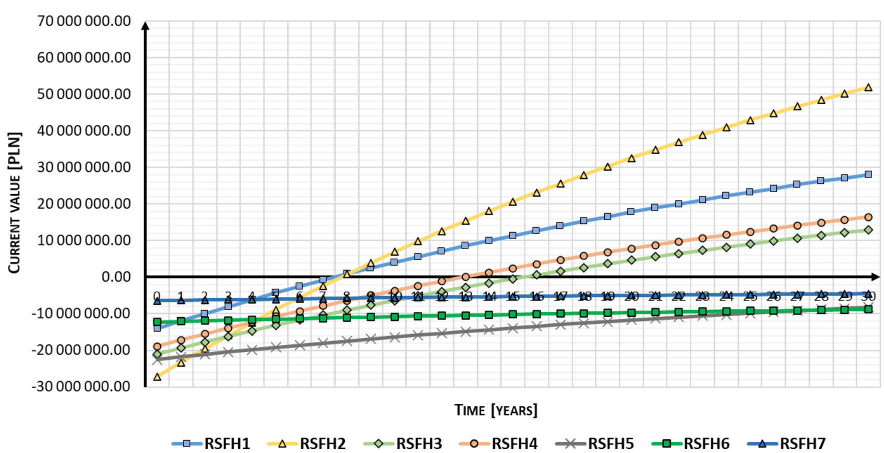


Figure A.18. *NPV analyses of the **V2** scenario for all building types in the analysed BC no. 2 located in Szczecin*

A.8.3. BUILDING CLUSTER NO. 3

In this section, some supplementary results for the BC no. 3 (which is presented in section **4.3**) are shown. An energy mapping, as well as the environmental aspects, have been already discussed. Therefore, in this section only heating LDCs are shown, for both examined localization, accordingly Wroclaw in **Figure A.19** and Bialystok in **Figure A.20**. All the proposed modernizations improved the overall energy efficiency of the examined region, regardless of the localization. Moreover, the obtained heating demand is more uniform, which is highly beneficial in terms of local grid safety and its reliability. Also, the annual average demands are much lower for the modernized scenarios compering with the base variant.

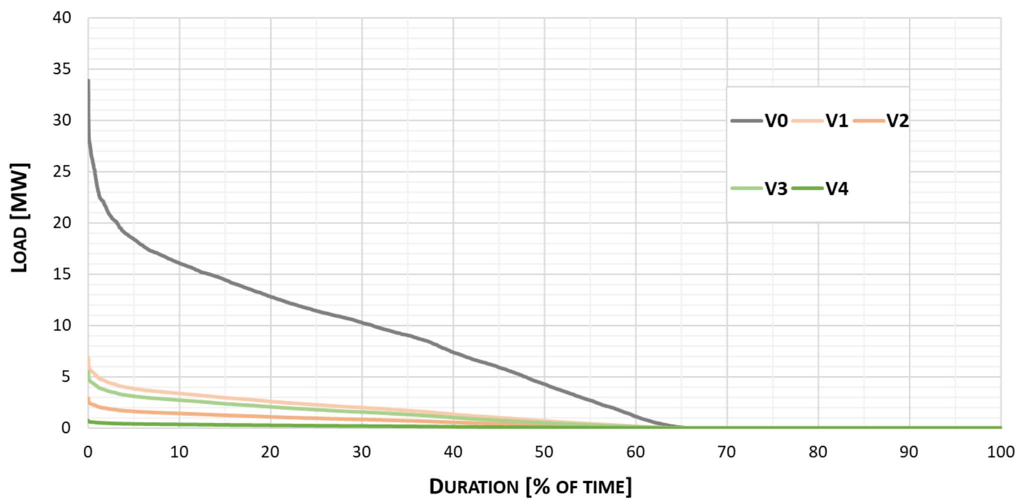


Figure A.19. *Heating LDCs for the BC no. 3 located in Wroclaw*

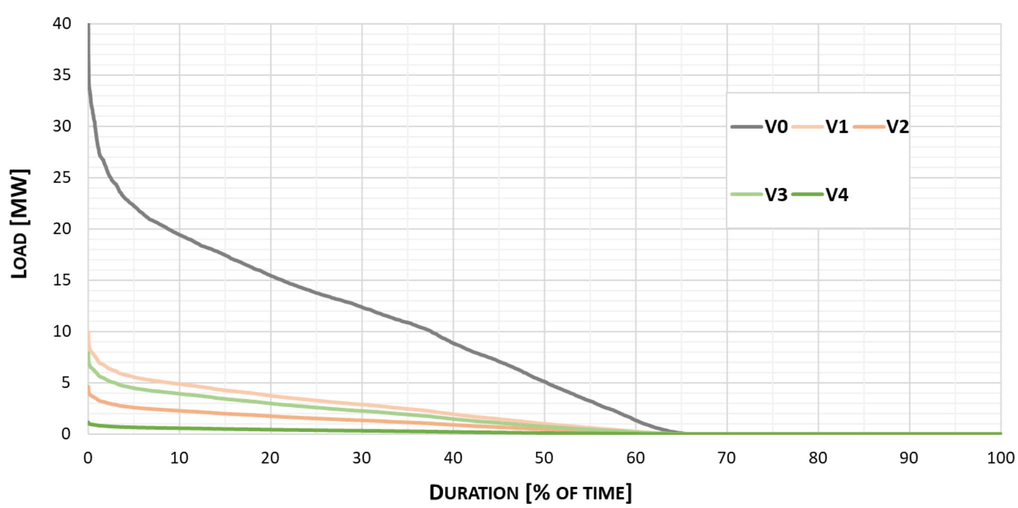


Figure A.20. *Heating LDCs for the BC no. 3 located in Bialystok*