# USING MODULARITY FOR ENERGY RENOVATION OF RESIDENTIAL BUILDINGS

Michaela Žďárská*,[1], Michal Kabrhel[1]

* michaela.zdarska@fsv.cvut.cz
[1] Czech Technical University, Faculty of Civil Engineering, Thákurova 2077/7, 166 29 Praha 6, Czech Republic

**Abstract**

The article deals with the search for a cost-optimal deep renovation of an existing residential building, which best represents the existing housing stock in the Czech Republic. The energy part of the deep renovation is designed using renewable energy sources in the form of modular energy systems. It is an application of the principles of modular construction to the building services, in order to achieve faster, higher quality and cheaper reconstruction of standardized buildings.

**Keywords**

Energy renovation, modularity, modular energy systems, renewable energy sources, residential buildings

# 1 INTRODUCTION

The building sector accounts for over 40% of global energy consumption, with the majority derived from non-renewable sources such as natural gas, coal, and other fossil fuels [1]. This form of energy production is inherently unsustainable due to its dependence on finite natural resources and its significant contribution to environmental degradation, particularly through the emission of greenhouse gases. Currently, only 17% of the national renewable energy share is attributed to large-scale renewable energy installations, including photovoltaic systems, hydroelectric power plants, and wind farms [2].

The current construction trend and legislative requirements place emphasis on new development using the least amount of energy and encourage the design of renewable energy sources (RES). In addition to zero-emission new buildings, it is essential to meet the requirements of the new European Directive EBPD4 to approach refurbishments with energy consumption which far exceeds that of new buildings in this way. The aim of this directive is to make all buildings zero-emission by 2050, including existing buildings [3].

The energy consumption of the building stock depends on the age of the building, climatic conditions and the way of its use. Around 35% of the building stock in the EU is over 50 years old, more than 40% of the building stock was built before 1960 and 90% before 1990, of which almost 75% are energy inefficient according to current building standards. The current annual rate of energy retrofitting corresponds to only 1% of the building stock. However, renovation of existing buildings can lead to substantial energy savings and is an essential element in achieving zero-emission buildings. Notably, energy performance regulations targeting at the thermal insulation properties of building envelopes were not widely introduced across Europe until after the 1970s. Consequently, a significant portion of the current building stock lacks fundamental thermal performance measures and on the other hand will continue to constitute a substantial share of the housing stock in the forthcoming decades due to its long service life [3], [4].

## Present state references

This paper explores cost-optimal strategies for deep renovation, emphasizing the application of modular construction principles. Special attention is given to the integration of renewable energy technologies in the renovation of residential buildings to reduce operational energy demand and associated greenhouse gas emissions.

The reduction of energy consumption can be achieved in many ways, either by improving the thermal performance of the building envelope or by designing energy-saving measures for the building services. The ideal situation is a combination of both approaches in the best possible optimisation. The combination of both approaches

Received 07/02/2025/Accepted 10/06/2025/Published30/09/2025 DOI 10.13164/juniorstav.2025.26099

is called deep or robust renovation. These measures should include the incorporation of renewable energy sources. The benefits of deep renovation are energy savings, financial savings, greenhouse gas savings and improved indoor environment for building occupants. Deep retrofits can be time-consuming and investment intensive, especially if they are purely concerned on energy savings and do not take into account the needs and capabilities of the occupants, market energy prices or return on investment. They are also very complicated to carry out with the occupants staying in the building. These facts lead to the search for cost and time-optimal solutions for robust retrofits [5]. One solution could be the use of modular principles in deep and energy renovations.

Modularity is the assemblability of blocks or components and is mainly associated with the prefabrication of building parts, structural components or complete building cells. Production takes place off-site, the element is then transported and placed on-site. The general advantages of modular construction are time savings during construction or renovation, a more controlled production process under quality conditions, the use of automated machinery, the use of repetitive processes, reduced waste production, and a reduction in negative impacts such as noise and clutter on the building site. However, there are also a number of disadvantages associated with the use of modularity, such as more thorough pre-project planning or more complex transport of modules to the construction site in case of bulky components [6]

# 2 METHODOLOGY

The research method included research into existing knowledge on the design options for modular energy systems in existing buildings and real-life cases used mainly in Europe. An analysis of the existing condition was carried out for a typical existing building and elements for deep renovation were recommended. Special emphasis was given to the energy renovation part using modular energy systems so that the solution is repeatable for a typical existing building.

The definition of the existing housing stock was made specifically for the Czech Republic. The sample case of existing housing stock, on which the concept of using modular energy systems ewas applied, was based on the TABULA project [7] and data from the Czech Statistical Office [8]. The sample building was selected as the most typical of the existing residential development, in terms of its construction, period of construction and space for the placement of new technical and energy equipment. A mathematical model of the actual building was developed using the NKN calculation tool [9]. Subsequently, the model was optimized in terms of the thermal-technical properties of the building envelope to meet the requirements for a passive building given by the ČSN 73 0540-2 standard [10]. The mathematical model developed in this way was analysed to determine and compare the energy demand under different possibilities of using new technical and energy systems. Emphasis was placed especially on the use of renewable energy sources, reduction of energy needs of the residential building and overall implementation of a solution that meets the criteria for emission-free buildings given by the European Directive EBPD4 [3].

The premise of this study was to use the principles of modular construction to achieve a cost-optimal deep energy renovation. It concluded by proposing a concept of modular energy systems for the use in a typical exemplary existing development. In particular, renewable energy sources and technical systems were used to reduce the energy consumption of the residential building, reduce greenhouse gas emissions and reduce the overall cost of living.

# 3 RESULTS

Modularity can be applied in power systems, for example, by assembling several devices into one compact module. The design of energy systems in modules makes it possible to expand and connect energy sources, storage systems and other parts of technical systems according to the specific requirements of the building. When combining multiple modules, each module should be independently interchangeable. A module assembled in this way also has limitations, for example in terms of its location. The project dealt with the refurbishment of existing residential building in which there was limited space for the installation of new technical systems. In most cases, it was necessary to use the building itself for the placement of the energy modules - the building shell, technical spaces such as installation shafts, and other attic or cellar spaces. In most cases, the outside area was not available as it does not belong to the owners of the housing units.

DOI 10.13164/juniorstav.2025.26099

## Analysis of the existing condition of the residential building and design of a cost-optimal deep renovation

The following section is devoted to the analysis of an existing residential building, selected based on the above-described procedure and the design of an optimized solution for deep renovation. It is a prefabricated building, built in 1963, which underwent a partial reconstruction of the building envelope in 2000. The heating and hot water is provided by district heating. The heat source is a hot water heat exchanger connected to the district heating pipe in the basement of the building, it is not an efficient district heating system according to the law [10]. Ventilation is designed only as under-pressure from fans in the bathroom and kitchen hood. The building currently does not meet the requirements for modern building according to the ČSN 73 0540-2 standard [11], it consumes a considerable amount of energy for its operation, and the indoor microclimate is not very comfortable for its users. For example, there are frequent exceedances of the permitted $CO_2$ concentration limit set by Decree No 268/2009 Coll. in the living rooms [12].

In the study, 2 solutions were designed to improve the building envelope, which included additional insulation of the normal passive house value marked as the standard solution. The second proposal involved insulation to the higher values of the passive design, replacing the existing double-glazed windows with triple-glazing. The observed current values of the housing stock surveyed, the requirements for design measures and the associated thermal insulation thickness are described in Table 1 and Table 2. In both cases, a forced ventilation system with heat recovery was added, with an efficiency of 80%. (see Table 3). It shows the savings of the designed measures in the form of average heat transfer coefficients and in the form of the ratio of saved supplied energy to the building. The first designed solution resulted in a 40.8% saving in energy delivered to the building, and the second design resulted in a 45.7% saving. When presenting the results on the average heat transfer coefficient, the first case of the standard solution had a value of $U_{em}$ = 0.46 W/m$^2$.K, the design of the progressive solution brings the value to $U_{em}$ = 0.34 W/m$^2$.K.

Tab. 1 Identified parameters of the current state of buildings in the surveyed housing stock in the Czech Republic and design measures.

| Element | Current U [W/m$^2$.K] | Standard U [W/m$^2$.K] | Progressive U [W/m$^2$.K] |
|---|---|---|---|
| **Wall** | 1.20 – 0.35 | 0.18 | 0.12 |
| **Roof** | 0.95 – 0.24 | 0.12 | 0.10 |
| **Ceiling under unheated attic** | 1.80 – 0.32 | 0.16 | 0.10 |
| **Floor above basement** | 1.65 | 0.26 | 0.20 |
| **Floor on the ground** | 2.00 | 0.26 | 0.15 |
| **Windows** | 2.40 – 1.50 | 1.20 | 0.90 |
| **Doors** | 2.60 – 1.70 | 1.20 | 0.90 |

Tab. 2 Insulation thicknesses corresponding to the requirements in Tab. 1.

| Element | Current Situation | Standard measures | Progressive measures |
|---|---|---|---|
| | Thermal insulation thickness [mm] | | |
| **Wall** | 0 – 80 | 160 | 240 |
| **Roof** | 0 – 180 | 280 | 300 |
| **Ceiling under unheated attic** | 0 – 140 | 200 | 300 |
| **Floor above basement** | 0 | 120 | 180 |
| **Floor on the ground** | 0 | 120 | 200 |

Tab. 3 Comparison of the existing situation with the designed measures.

| Renovation indicators | Current situation | Standard measures | Progressive measures |
|---|---|---|---|
| **$U_{em}$ [W/m$^2$.K]** | 1.0 – 0.84 | 0.46 | 0.34 |
| **Saving supplied energy [%]** | 0 | 40.8 | 45.7 |

DOI 10.13164/juniorstav.2025.26099

## The concept of modular energy systems

The design of the energy system was approached to meet the requirement of zero-emission energy sources according to the law [10] and at the same time, renewable energy sources were used. A combination of air-to water heat pumps, photovoltaic panels and forced air conditioning system with heat recovery was selected as an example of a possible design of suitable energy systems for the reconstruction of prefabricated houses. Another option for a zero-emission energy source could be to retain the existing district heating with a change to efficient district heating. However, this change is long-term and does not depend on an immediate decision by investors. Moreover, the initial phase of this research which looked at the complete emissions of the sources, including embodied ones, showed that the actual emissions of efficient district heating could be higher than the designed set of renewable energy sources [13]. A simplified calculation of embodied emissions was based on the online KBOB database [14].

The building envelope and the construction of the loggia railing facing south are used for the placement of PV modules. As shown in Fig. 1, PV modules on the railing are installed only from the 3rd floor upwards. This placement considers the mature vegetation in the vicinity of the model building. This would be the same for the vast majority of buildings assessed in this study. Additional PV modules are located on the roof facing south-east and north-east with a 30° pitch. The choice and extent of this PV placement reflect the findings of previous work [15].

The roof also houses an assembled modular box with pre-prepared systems for the heat pump and ventilation units. An example is shown in Fig. 1, Fig. 2, and Fig 3. The roof and facade of the building are also the most common potential spaces to be used for the installation of new energy systems across all the buildings studied.

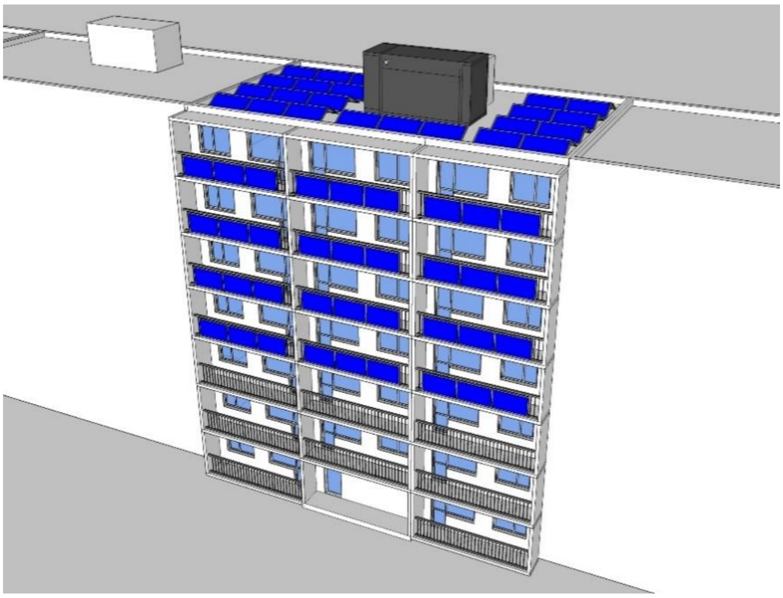

Fig. 1 Location of the energy system modules on the model building.

DOI 10.13164/juniorstav.2025.26099

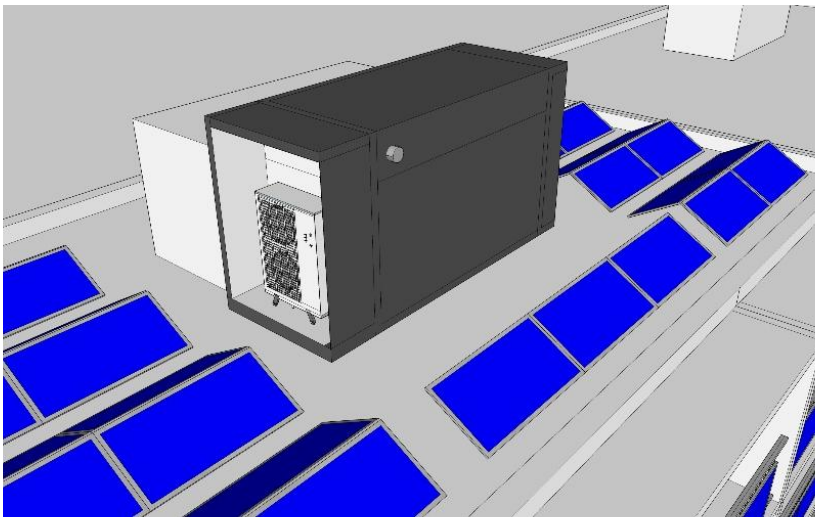

Fig. 2 Modular box with placement of power systems. View of the closed box.

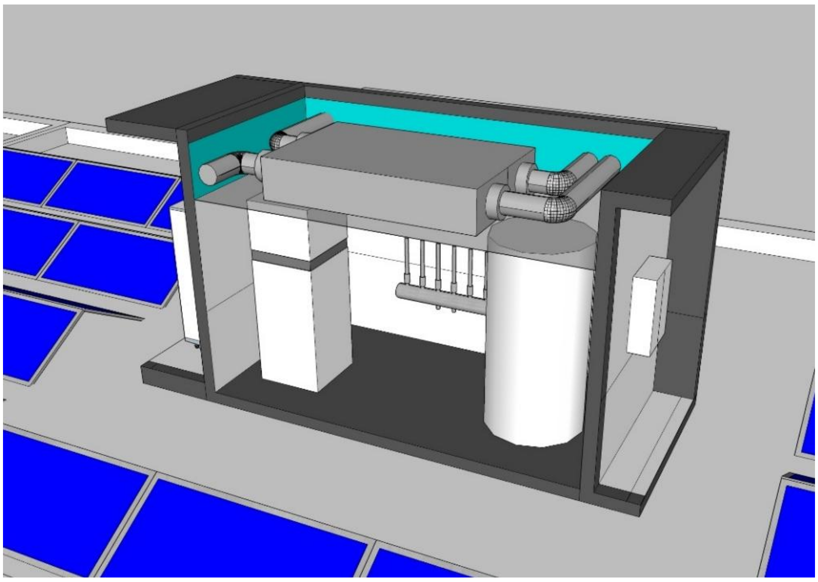

Fig. 3 Modular box with the location of power systems. View of the open box.

The range of PV panels designed in this way corresponds to the use of about 1/3 of the building envelope and covers up to 25% of the total annual electricity consumption. In this case, in addition to the energy consumption in the common areas, consumer energy, which is not a common part of energy balances, was also calculated and derived from TDD-type supply diagrams [16]. The common area use, lighting, lift operation and forced-air consumption were considered, this proposal would cover the entire consumption with a significant surplus that could be distributed further. The PV production was calculated in an hourly steps for the area of the model building location in Prague using the online application PVGIS [17]. An air-to-water heat pump design of this size can cover the complete consumption of thermal energy for hot water and heating. In the case of this model building, the areas and spaces of the building are used to almost the maximum extent possible to identify opportunities. The next step of the project will be to address the optimization of modular systems, their subdivision or addition. The possibility of combining existing resources with the addition of modular technical and energy systems will also be considered.

DOI 10.13164/juniorstav.2025.26099

# 4 DISCUSSION

The two designs - standard and progressive - are very similar in terms of energy inputs and the design of suitable energy systems for these designs are very different. The same solutions can be used, in the same combinations, which would mean, for example, only higher or lower outputs of the energy sources used. Whether the insulation is standard or higher passive, it is appropriate to consider the addition of air-handling equipment to provide a good indoor microclimate, which ensures a substantial reduction in heat loss through ventilation. The savings values of the standard and progressive solutions are compared with the existing situation. Although the difference in the average heat transfer coefficient $U_{em}$ was up to 15% when comparing standard vs. progressive, when comparing the total energy delivered, it is only a third of the savings, around 5%. The results therefore show that it may not always be advantageous to design an extremely deep renovation solution that maximally reduces the energy needs of the building. In this case, the design of a progressive solution would result in the replacement of the still functioning windows, and a significant increase in the thickness of the building envelope thermal insulation, but with almost minimal impact on the final energy needs of the building and on the possibility of using other energy systems. These findings confirm, for example, the conclusions presented in the article [5].

The problem with the placement of energy modules can be the load-bearing capacity of existing structures. The final solutions always have to be assessed by a structural engineer and the structures for the placement of the designed modules must be modified or supplemented with a suitable technical design if necessary. During the research for this study, the addition of new structural elements such as self-supporting balconies was often part of the deep renovation carried out [18]. These solutions can also be included among the modular elements of the renovation and placed either on their own or with the addition of energy modules. The reconstruction of the roof cladding can be considered with an extension and the creation of new spaces for the installation of energy and technology modules in the same way. [19].

Other difficulties, not of a construction nature, may be caused by the owners of some flats in the case of in-depth reconstruction of residential buildings. Joint consent of unit owners is not easy to obtain. The renovation would mean a significant reduction in energy costs, in some cases up to 50%, and an improvement in the quality of the indoor environment. The upfront investment may be high, but the profitability of the renovation is determined by the payback. This typically ranges between 10-15 years if it is purely insulation and replacement of fenestration; if energy renovation is included, the payback period is reduced to 8-12 years depending on the scale of the investment, the solution used and the initial condition (realistic payback period is considered) [15]. Both time horizons are acceptable in the case of residential buildings. On the other hand, the whole process of complex renovation, including the placement of new energy systems, can be challenging and can constrain flat owners for some time. The use of modular systems can offer some acceleration of the whole process and a reduction in the restrictions during the renovation.

Integrated approaches at the area or neighbourhood level help to increase the cost-effectiveness of renovations needed for buildings that are spatially connected, such as apartment blocks. Such approaches to renovations offer different solutions on a larger scale [3].

# 5 CONCLUSION

Given the number of existing residential buildings built before 1990 and the long service life of the structures themselves, it is advantageous to use optimally cost-effective deep reconstruction and reconstruction in general as much as possible, while considering the needs and possibilities of investors. The current annual rate of such renovations is too low and the existing condition of the residential buildings is in most cases unsatisfactory in terms of high energy consumption, associated high housing costs, high greenhouse gas production and low comfort of the flat occupants [3], [4].

Modularity used either in pure energy system design or in complex deep reconstruction, for example in the form of insulation panels, could make reconstruction more efficient and shorter, and with the possibility of repeatability of solutions using typical categories of residential buildings, it could become cheaper than unique designs carried out separately for each building, even though it would be the same type category.

Research has demonstrated the justification for deep renovations with optimised thermal engineering. Another important finding is that one of the most common residential buildings in the housing sector in the Czech Republic can be self-sufficient to provide heating and hot water, using purely renewable energy sources, and only its own

DOI 10.13164/juniorstav.2025.26099

area and spaces are sufficient for this. At the same time, the building is capable of producing a significant amount of electricity, either for its own operation or ¼ for all user consumption.

The field of this research can be extended to include other designs for buildings of different types, which make up another significant proportion of the existing housing stock. Alternatively, additional energy systems can be designed within technical and energy modules, ideally using renewable energy sources. In addition to the environmental side, for an overall sustainable renovation design, it is also important to focus on the economic and social side and ideally optimize deep retrofit accordingly.

## Acknowledgements

This paper is based on a project developed with the support of the CTU student grant competition. Grant number: SGS24/012/OHK1/1T/11 and SGS25/013/OHK1/1T/11

## References

[1] FOCUS – Energy efficiency in buildings [online]. 17 Feb 2020 [cited 29 Apr 2025]. Available from: https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en

[2] MINISTRY OF INDUSTRY AND TRADE. [online]. 2022 [cited 29 Apr 2025]. Available from: https://www.mpo.cz/cz/energetika/energeticka-ucinnost/prohlaseni-k-vyuzivani-hourly-climatic-data-for-energy-costs-of-buildings--270834/

[3] EUROPEAN UNION. Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on Energy Performance of Buildings (recast) [online]. 2024 [cited 29 Apr 2025]. Available from: https://eur-lex.europa.eu/legal-content/CS/ALL/?uri=CELEX:32024L1275

[4] FILIPPIDOU, F. and JIMENEZ NAVARRO, J. Achieving the cost-effective energy transformation of Europe's buildings. EUR 29906 EN. Luxembourg: Publications Office of the European Union, 2019. ISBN 978-92-76-12393-4. Available from: https://publications.jrc.ec.europa.eu/repository/handle/JRC117739

[5] GALIMSHINA, Alina, Maliki MOUSTAPHA, Alexander HOLLBERG, Pierryves PADEY, Sébastien LASVAUX, Bruno SUDRET and Guillaume HABERT. What is the optimal robust environmental and cost-effective solution for building renovation? Not the usual one. Energy and Buildings [online]. 2021, 251, 111329. ISSN 0378-7788. Available from: https://doi.org/10.1016/j.enbuild.2021.111329

[6] KAMALI, Mohammad and Kasun HEWAGE. Life cycle performance of modular buildings: A critical review. Renewable and Sustainable Energy Reviews [online]. 2016, 62, pp. 1171–1183. ISSN 1364-0321. Available from: https://doi.org/10.1016/j.rser.2016.05.031

[7] TABULA PROJECT. Handbook of typologies of residential buildings with examples of measures to reduce their energy performance: Czech Republic. Updated 2014 [online]. Available from: https://episcope.eu/fileadmin/tabula/public/docs/brochure/CZ_TABULA_TypologyBrochure_STU-K.pdf

[8] CZECH STATISTICAL OFFICE. Census of Population, Houses and Flats [online]. 2022 [cited 29 Apr 2025]. Available from: https://csu.gov.cz/scitani-2021?pocet=10&start=0&podskupiny=171&razeni=-datumVydani

[9] NKN National Calculation Tool. © Department of Building Engineering, Faculty of Civil Engineering, CTU in Prague, 2021 [online]. Available from: http://nkn.fsv.cvut.cz/

[10] CZECH REPUBLIC. Act No. 165/2012 Coll., on Supported Energy Sources and on Amendments to Certain Acts (the Supported Energy Sources Act), as amended. 2012.

[11] ČSN 73 0540-2. Thermal protection of buildings – Part 2: Requirements. Prague: Centre for Technical Standardization, Faculty of Civil Engineering, Czech Technical University in Prague, 2011.

[12] CZECH REPUBLIC. Decree No. 268/2009 Coll., Decree on technical requirements for buildings. Prague: MMR, 2009.

[13] ŽĎÁRSKÁ, M. and M. KABRHEL. Use of modular energy systems to achieve zero emissions in residential buildings. In: Proceedings of 22nd Summer School of TZB 2024 – TZB for zero emission buildings conference. 11–13 Sep 2024, Byňov, Nové Hrady. Prague: Society for Environmental Technology, 2024, pp. 78–83. ISBN 978-80-02-03060-7.

[14] KOORDINATIONSKONFERENZ DER BAU- UND LIEGENSCHAFTSORGANEN DER ÖFFENTLICHEN BAUHERREN (KBOB). KBOB – Startseite [online]. Bundesamt für Bauten und Logistik BBL, [cited 13 Jun 2024]. Available from: https://www.kbob.admin.ch/kbob/de/home.html

[15] ŽĎÁRSKÁ Michaela. Návrh obnovitelných zdrojů pro bytový dům [online]. Praha, 2023. Master's thesis. Czech technical university in Prague, Faculty of Civill Engeneering. Supervisor: doc. Ing. Michal KABRHEL, Ph.D., Available from: https://dspace.cvut.cz/handle/10467/110634

[16] OTE. Standardized Load Diagrams of Electricity Supply [online]. 2022 [cited 28 Mar 2023]. Available from: https://www.ote-cr.cz/cs/statistika/typove-diagramy-dodavek-elektriny/normalizovane-tdd?date=2022-12-01

[17] EUROPEAN COMMISSION. PVGIS – Photovoltaic Geographical Information System [online]. [cited 29 Apr 2025]. Available from: https://re.jrc.ec.europa.eu/pvg_tools/en/

[18] THOMSEN, Kirsten Engelund, Jørgen ROSE, Ove MØRCK, Søren ØSTERGAARD JENSEN, Iben ØSTERGAARD, Henrik N. KNUDSEN and Niels C. BERGSØE. Energy consumption and indoor climate in a residential building before and after comprehensive energy retrofitting. Energy and Buildings [online]. 2016, 123, pp. 8–16. ISSN 0378-7788. Available from: https://doi.org/10.1016/j.enbuild.2016.04.049

[19] POJAR, Petr. We are creating more flats by extending the apartment building [online]. www.ceskestavby.cz, 24 Nov 2024 [cited 29 Apr 2025]. Available from: https://www.ceskestavby.cz/clanky/nastavbou-bytoveho-domu-vytvorime-dalsi-byty-23149.html