Form DrS1

Sveučilište u Rijeci • University of Rijeka
Trg braće Mažuranića 10 • 51 000 Rijeka • Croatia
T: +385 (0)51 406-500 • F: +385 (0)51 216-671; +385 (0)51 216-091
W: www.uniri.hr • E: ured@uniri.hr

REQUEST FOR APPROVAL OF THE PhD THESIS TOPIC

General information and PhD candidate contact information	
Title, first and last name of the PhD candidate	Lorena Dabac
Provider(s) of the study programme	University of Rijeka, Faculty of Economics and Business
Name of the study programme	PhD study Economics and Business Economics
Identification number of the PhD candidate	
First and last name of mother and/or father	
Date and place of birth	
Address	
Telephone/mobile phone number	
E-mail	lorena.dabac@efri.uniri.hr

1. TITLE OF THE PROPOSED TOPIC
1.1. Croatian
Tržišno utemeljen poslovni model održive energetske obnove javnih zgrada
1.2. English
A Market-Based Business Model for Sustainable Energy Renovation of Public Buildings
1.3. Area/field
Social Sciences / Economics

2. PROPOSED OR POTENTIAL SUPERVISOR(S)		
2.1. Supervisor(s)		
Title, first and last name	Institution, country	E-mail
Prof. Ivana Tomas Žiković, PhD	University of Rijeka, Faculty of Economics and Business	*ivana.tomas.zikovic@efri.uniri.hr*

Minimal general criteria for supervisor selection:

- *has to hold a PhD degree and be awarded a scientific rank,*
- *has to have at least two years of postdoctoral experience,*
- *has to have a lead (co-lead or partner) position in a national or international project, or in some other way be able to ensure support for scientific research,*

- *has to satisfy the minimal criteria of excellence.*

If the supervisor is not an employee of the University of Rijeka, a co-supervisor from the University's constituent unit implementing the postgraduate study programme is assigned to the PhD candidate.

2.2. Co-supervisor

Title, first and last name	Institution, country	E-mail
Prof. Alberto Ferraris, PhD	University of Turin	*alberto.ferraris@unito.it*

3. TOPIC OUTLINE

3.1. Summary in Croatian
(no more than 1000 characters with spaces)

Zgrade su među ključnim područjima energetske tranzicije jer visoka i dugotrajna potrošnja energije u zgradarstvu istodobno stvara fiskalni pritisak, povećava emisije i produbljuje izloženost volatilnim cijenama energije. U tom kontekstu energetska obnova javnih zgrada nije samo tehničko pitanje, nego i ekonomski problem oblikovanja poticaja, raspodjele rizika i izbora održivog investicijskog modela. Dosadašnja istraživanja pokazuju da ulaganja u energetsku učinkovitost često ograničavaju tržišni neuspjesi, informacijske asimetrije, podijeljeni poticaji i otežan pristup financiranju, zbog čega potencijal energetski isplativih ulaganja ostaje nedovoljno iskorišten.

Predloženo istraživanje polazi od Republike Hrvatske kao studije slučaja i oslanja se na podatke iz Informacijskog sustava za gospodarenje energijom (ISGE), prikupljene posredstvom Agencije za pravni promet i posredovanje nekretninama (APN), za 11.426 zgrada u javnom vlasništvu u razdoblju od 2020. do 2025. godine. Baza obuhvaća informacije o lokaciji, vrsti objekta, površini, potrošnji energije, jediničnom trošku energenata, primarnoj energiji i emisijama CO_2. Cilj je utvrditi obrasce potrošnje i emisija u javnom fondu zgrada, identificirati ekonomske i prostorne odrednice energetske potrošnje te procijeniti u kojoj se mjeri različiti modeli obnove mogu opravdati s aspekta troška, ušteda i šireg gospodarskog učinka. Poseban naglasak stavlja se na razlike među tipovima zgrada, energentima i županijama te na procjenu troškova obnove po energetskim razredima i dubini obnove.

Metodološki, istraživanje je organizirano u dvije glavne analitičke cjeline. U prvom dijelu primijenit će se panel-analiza determinanti potrošnje energije i emisija CO_2, pri čemu će se koristiti panel-model s Mundlakovom korekcijom, odnosno correlated random effects/within-between random effects pristup, kojim će se identificirati i razdvojiti učinci promjena unutar iste zgrade kroz vrijeme od učinaka strukturne heterogenosti među zgradama. Prednost ovoga pristupa jest mogućnost istodobne procjene učinaka vremenski promjenjivih varijabli i vremenski nepromjenjivih obilježja, poput tipa zgrade, vrste energenta i regije, što ga čini metodološki prikladnim za analizu heterogenosti i dinamike u potrošnji energije i obrascima obnove javnih zgrada (Mundlak, 1978; Bell i Jones, 2015). U drugom dijelu empirijskog rada provest će se scenarijska analiza troškova obnove prema energetskim razredima i dubini zahvata radi procjene financijske opravdanosti integrirane i dubinske obnove.

U teorijskom smislu rad se oslanja na literaturu o energetskom jazu učinkovitosti, internalizaciji eksternalija i tržišno utemeljenim instrumentima za smanjenje emisija. Dosadašnja istraživanja upozoravaju da sama tehnička izvedivost obnove nije dovoljna bez financijskih modela koji mogu mobilizirati kapital i raspodijeliti koristi među državom, investitorima i korisnicima. Upravo je tu istraživačka praznina: literatura obiluje analizama energetske učinkovitosti, ESCO modela (modeli koje provode tvrtke za energetske usluge), energetskog ugovaranja i certifikata ušteda, ali nedostaje radova koji te elemente povezuju u jedinstven, financijski održiv okvir primjenjiv na javne zgrade. Znanstveni doprinos predloženog rada sastoji se u razvoju integriranog tržišnog modela održive energetske učinkovitosti za javne zgrade, u kojem se energetske i CO_2 uštede, troškovi obnove, tržišni instrumenti i makroekonomski učinci promatraju kao međusobno povezane sastavnice jedne investicijske logike. Očekuje se da će rezultati ponuditi empirijski utemeljenu osnovu za vrednovanje isplativosti obnove javnih zgrada u Hrvatskoj te dati šire primjenjive spoznaje za oblikovanje održivih modela financiranja u europskom sektoru zgradarstva.

Ključne riječi: održivost, emisije CO_2, energetska učinkovitost, modeli temeljeni na tržišnim mehanizmima, financijska održivost, sektor zgradarstva

3.2. Summary in English
(no more than 1000 characters with spaces)

Buildings are a key area of the energy transition because high and long-term energy consumption in the building sector simultaneously creates fiscal pressure, increases emissions, and heightens exposure to volatile energy prices. In this

context, the energy renovation of public buildings is not only a technical issue but also an economic challenge involving the design of incentives, allocation of risks, and selection of a sustainable investment model. Previous research shows that investments in energy efficiency are often constrained by market failures, information asymmetries, split incentives, and limited access to finance, so the potential of cost-effective energy investments remains underutilised.

The proposed research uses the Republic of Croatia as a case study and relies on data from the Energy Management Information System (ISGE), collected through the Agency for Transactions and Mediation in Immovable Properties (APN), for 11,426 publicly owned buildings from 2020 to 2025. The database includes information on location, building type, floor area, energy consumption, unit cost of energy sources, primary energy, and CO_2 emissions. The aim is to determine patterns of consumption and emissions in the public building stock, identify the economic and spatial determinants of energy consumption, and assess the extent to which different renovation models can be justified from the perspective of cost, savings, and broader economic impact. Special emphasis is placed on differences among building types, energy sources, and counties, as well as on estimating renovation costs by energy class and level of construction intervention.

Methodologically, the research is organised into two main analytical units. In the first part, a panel analysis of the determinants of energy consumption and CO_2 emissions will be applied, using a panel model with Mundlak correction, that is, a correlated random effects/within-between random effects approach, which will identify and separate the effects of changes within the same building over time from structural heterogeneity among buildings. The advantage of this approach is the ability to estimate simultaneously the effects of time-varying variables and time-invariant characteristics, such as building type, energy source, and region, making it methodologically suitable for analysing heterogeneity and dynamics in energy consumption and renovation patterns of public buildings (Mundlak, 1978; Bell and Jones, 2015). In the second part of the empirical work, a scenario analysis of renovation costs according to energy class and depth of intervention will be carried out to assess the financial justification of integrated and deep renovation.

Theoretically, the dissertation draws on literature concerning the energy efficiency gap, the internalisation of externalities, and market-based instruments for reducing emissions. Previous research indicates that technical feasibility alone is insufficient without financial models capable of mobilising capital and distributing benefits among the state, investors, and users. This is precisely where the research gap lies: although the literature includes many analyses of energy efficiency, ESCO models (models implemented by Energy Service Companies), energy contracting, and energy savings certificates, there is a lack of studies that integrate these elements into a single, fiscally sustainable framework applicable to public buildings. The scientific contribution of the proposed doctoral research lies in developing an integrated market-based model of sustainable energy efficiency for public buildings, in which energy and CO_2 savings, renovation costs, market instruments, and macroeconomic effects are treated as interconnected components of a single investment logic. The results are expected to provide an empirically grounded basis for evaluating the cost-effectiveness of renovating public buildings in Croatia and to offer more broadly applicable insights for designing sustainable financing models in the European building sector.

Keywords: sustainability, CO_2 emissions, energy efficiency, market-based models, financial sustainability, building sector

3.3. Introduction and overview of previous research
(suggested length: 7000 characters with spaces)

The decarbonisation of the building stock in the European Union is increasingly shaped by a combination of regulatory requirements, technical standards and financial constraints. In this context, Maduta *et al.* (2023) show that the Energy Performance of Buildings Directive (EPBD) plays a key role in guiding Member States towards climate neutrality, but also that the implementation of its requirements remains uneven, particularly regarding long-term renovation strategies, standards for Nearly Zero-Energy Buildings (nZEB), energy certificates and inspections of technical systems. Although the authors estimate that implementing existing plans could significantly reduce energy consumption and direct emissions by 2050, they also warn that renovation rates and cross-country differences remain serious obstacles to achieving these goals. On this basis, Attia (2022) focuses on the Eastern European context and shows that understanding of the nZEB standard remains limited by the lack of comparable national data. His contribution lies in establishing an evidence base for ten Eastern European countries, covering energy efficiency thresholds, shares of renewable sources, requirements for the building envelope, ventilation, thermal comfort and market indicators such as heat pump penetration. The financial dimension of this process is further emphasised by Keliauskaite *et al.* (2025), who show that the current pace of renovation and deployment of clean heating systems is insufficient to achieve the EU's climate goals. Their analysis estimates that an investment of approximately EUR 298 billion per year is needed to reach the EPBD targets by 2030, with an annual investment gap of around EUR 149 billion. The same paper also presents data for Croatia, according to which the annual investment gap amounts to around EUR 0.3 billion, with potential annual savings of around EUR 0.2 billion, reducing the remaining gap to approximately EUR 0.1 billion. Taken

together, these papers show that the decarbonisation of buildings is not only a technical or regulatory issue, but also one of capital mobilisation, incentive design and the removal of market barriers.

Building on this, the literature further explains why energy-efficient investments are not implemented at the desired scale. Allcott and Greenstone (2012) place this problem within the framework of the energy efficiency gap and market failures, emphasising the importance of negative externalities, information asymmetries, principal-agent relationships and financial constraints. In the public buildings sector, these problems are further reinforced by budgetary rules, fragmented asset management and the fact that the entity bearing the investment cost is not always the same as the entity that directly benefits from lower energy costs. Thus, in the literature, the energy renovation of public buildings is viewed less as a narrowly technical issue and more as a combination of energy economics, public finance and institutional design.

In theoretical terms, such problems can be further explained through several interconnected economic approaches. From the perspective of welfare economics and the theory of externalities, energy inefficiency and CO_2 emissions from buildings represent negative externalities because part of the social costs is not included in private decisions on energy consumption and investment in renovation. In this tradition, Pigou (1920) justifies public intervention through corrective taxes and incentives, while Coase (2013) shows that outcomes also depend on the institutional framework, the clarity of rights and the possibility of market exchange. This is particularly important as it explains the economic logic of regulatory instruments, emissions markets, and models for monetising energy and emissions savings. Another important stream of research concerns the determinants of energy consumption in public buildings. Previous studies show that consumption is shaped by building typology, area, climatic conditions, usage patterns, and the technical characteristics of the building. Fiaschi, Bandinelli and Conti (2012) and Ma *et al.* (2017) confirm that different categories of public buildings have different consumption patterns, while Zhang *et al.* (2022) further show that building type, outdoor temperature, construction characteristics and area are among the most influential variables in predicting consumption. Ouedraogo, Levermore and Parkinson (2012) and El-Darwish and Gomaa (2017) emphasise the importance of the climatic context, while Dall'O' and Sarto (2013) and Trovato, Nocera and Giuffrida (2020) warn that the assessment of renovation must include not only the potential for savings but also the cost-effectiveness of individual measures. Zekić-Sušac, Has and Knežević (2021) demonstrate that data-driven approaches can successfully identify dominant consumption patterns at the building portfolio level. This suggests that public buildings should not be regarded as a homogeneous category, but as a heterogeneous stock in which energy performance varies according to function, location, technical systems, and patterns of use.

Another strand of the literature focuses on the economic effects of energy renovation. In the case of Croatia, Mikulić, Bakarić and Slijepčević (2016) show that investments in the renovation of public and residential buildings can generate positive direct, indirect and induced effects on production, employment and public revenues. Mikulić and Keček (2021) broaden this perspective, showing that building renovation can have strong effects on gross value added and employment within the broader energy transition. Tuominen, Forsström and Honkatukia, (2013) and Hirvonen *et al.* (2022) confirm that the benefits of renovation extend beyond energy savings to include reduced emissions, lower external costs, and greater energy security, while also cautioning that the fiscal effects for the state are not always clear-cut. Costantini, Crespi and Paglialunga (2018) further highlight the importance of public policies for employment, while Gholamzadehmir *et al.* (2025) introduce the market dimension of renovation through effects on property values. The common finding of these studies is that building renovation should not be assessed solely through private profitability, but also through broader macroeconomic and social benefits.

For the proposed research, an important part of the literature concerns the institutional and financial models for implementing renovation. Fang, Miller and Yeh (2012) show that ESCO models can significantly reduce energy consumption and that public buildings, due to common ownership and similar consumption patterns, are suitable for project bundling. Fawcett, Rosenow and Bertoldi (2019) emphasise the importance of the Energy Efficiency Obligation Scheme (EEOS) as a regulatory framework for encouraging investment, but also note the limitations of these instruments in more expensive and deeper interventions. Li, Qiu and Wang (2014) stress that the cost of capital and financing structure strongly determine the volume of investment and contractual outcomes, while Shang *et al.* (2017) show that the choice of Energy Performance Contracting (EPC) model directly affects risk allocation and project success. Faggianelli, Mora and Merheb (2017) warn that the quality of baseline assessment and savings verification remains a key issue for the credibility of energy contracts. Successful renovation of public buildings therefore requires more than technically appropriate measures; it also depends on contractual arrangements, financing conditions, and credible procedures for measuring and verifying savings.

The literature most relevant to the key contribution of this dissertation addresses the verification and monetisation of energy and emissions savings. Afshari and Friedrich (2016), Newsham (2019), and Ahmadi *et al.* (2020) show that energy savings certificates, also known as white certificates, and related mechanisms can provide an additional source

of revenue beyond direct energy cost savings, while Giraudet and Finon (2015) and Bertoldi *et al.* (2010) emphasise that the effectiveness of such systems depends on verification rules, market design, and the actual possibility of trading. Existing research is well developed in three distinct areas: the determinants of energy consumption in buildings, ESCO/EPC models, and the market valorisation of savings. However, relatively little research has integrated these three areas into a single analytical framework for public buildings while simultaneously accounting for energy consumption, emissions, renovation costs, market incentives, and fiscal sustainability. Such a framework is particularly important in the Croatian context, as the proposed dissertation topic starts from the actual stock of public buildings and seeks to develop an integrated model through which energy and emissions savings would be transformed into a sustainable investment mechanism for the renovation of the public building stock.

An important theoretical foundation is transaction cost theory, which holds that economic outcomes depend not only on technology and relative prices, but also on the costs of contracting, monitoring, implementation, and verification (Williamson, 1981). This is directly applicable to the energy renovation of public buildings, where project success depends on the quality of contracts, risk allocation, measurement and verification of savings, and effective coordination between the public sector, contractors, and financial institutions. In this context, ESCO and EPC models, as well as market mechanisms for the valorisation of savings, can be seen as institutional responses to high transaction costs and investment uncertainty. For the fiscal dimension of the research, the theory of the double dividend provides an additional theoretical perspective, as it suggests that environmental instruments may, in addition to reducing emissions, generate further economic benefits when revenues or savings are used to finance investments and mitigate other distortions. This supports the view that the energy renovation of public buildings should be assessed not only in terms of private savings, but also in relation to broader public finance and development effects.

Existing studies typically examine the determinants of building energy consumption, the economics of renovation, or market-based financing instruments. However, they rarely integrate empirical building-level consumption and CO_2 data, renovation cost scenarios, monetisation of savings, and financial sustainability into a single analytical framework for public buildings.

3.4. Research aim and research hypotheses
(suggested length: 700 characters with spaces)

Despite extensive literature on energy efficiency, building decarbonisation, financial models for renovation, and market instruments for reducing emissions, there is still a lack of an integrated research framework connecting these areas at the level of the actual public building stock. An approach that simultaneously addresses patterns of actual energy consumption, CO_2 emissions, the heterogeneity of the public building stock, renovation costs, and the conditions for financial and fiscal sustainability of different implementation models has been insufficiently explored. The proposed dissertation aims to fill this research gap by developing an empirically grounded analytical framework for evaluating the energy renovation of public buildings at the system level.

The main objective of the dissertation is to empirically identify the determinants of energy consumption and CO_2 emissions in public buildings in the Republic of Croatia and, based on renovation scenarios and stochastic valuation of costs and benefits, to assess the conditions under which energy renovation can be financially justified and fiscally sustainable.

The following specific objectives arise from the main objective:

- Empirically analyse patterns of energy consumption and CO_2 emissions in public buildings with regard to building type, dominant energy source, location, size, and climatic conditions.
- Assess the impact of structural, spatial, and economic factors on energy consumption and CO_2 emissions in public buildings.
- Design scenarios for integrated and deep renovation of public buildings and assess their energy, emissions, and financial effects.
- Examine the extent to which the inclusion of energy and emissions savings, through the application of appropriate financial mechanisms, can improve the financial sustainability of investments in the renovation of public buildings.
- Based on empirical findings and scenario analysis, assess the conditions for designing a market-based and fiscally acceptable framework for financing the energy renovation of public buildings.

Research hypotheses:

(H1) Differences in energy consumption and CO_2 emissions among public buildings can be statistically explained by the structural characteristics of buildings, the type of energy source used, and the spatial and climatic context.

(H2) The energy renovation of public buildings can achieve positive energy and emission-related effects and be financially viable under certain combinations of investment costs, energy prices, and the level of achieved savings.

(H3) The inclusion of energy and emissions savings in the financing model for energy renovation improves the financial sustainability of projects and reduces the need for direct state incentives.

H1 will be tested using panel models of energy consumption and CO_2 emissions, while H2 and H3 will be examined through renovation scenarios and stochastic valuation of costs, savings, and financing effects.

3.5. Materials, methodology and research plan
(suggested length: 6500 characters with spaces)

The research will be based on a combination of administrative, energy, spatial and cost data, applying quantitative and scenario-based analytical methods. The primary empirical material consists of data from the restricted-access database of the Energy Management Information System (ISGE), access to which was provided through the Agency for Transactions and Mediation in Immovable Properties (APN). The database covers 11,426 publicly owned buildings in the Republic of Croatia from 2019 to 2025, with available data for each building on building code and location, building type, floor area, energy consumption, unit energy cost, total cost of all energy types used (in EUR), primary energy, and CO_2 emissions. The sample includes buildings owned by central government, local and regional self-government units, and other public bodies. The selection of the Republic of Croatia as the empirical framework is primarily due to the availability of detailed building-level microdata from the ISGE database, as such data are not publicly accessible elsewhere and access to comparable restricted-access databases for other countries was not possible. This research is therefore designed as an in-depth national case study, with its analytical value stemming from the use of longitudinal microdata at the level of individual public buildings rather than from cross-country comparison. Although the empirical analysis is based on the Croatian public building stock, the proposed analytical framework is designed in a way that may allow its application in other institutionally comparable contexts, subject to the availability of similar building-level data.

In addition to the ISGE database, supplementary datasets necessary for explaining the spatial, climatic and economic characteristics of energy consumption will also be used. These include data on climatic conditions, primarily heating indicators, as well as data on population density, regional characteristics, and the macroeconomic indicator of GDP per capita. In the final part of the research, bills of quantities for construction and energy renovation works will be used to estimate renovation costs by floor area (m^2), depending on the depth of intervention and the targeted energy class. Two renovation scenarios are envisaged in the dissertation: integrated and deep, with individual interventions linked to the transition of buildings from lower to higher energy classes.

Methodologically, the research will be conducted in several interconnected stages. In the first stage, a descriptive and exploratory analysis of the data will be undertaken to identify the basic patterns of energy consumption and CO_2 emissions in the public building stock. Buildings will be classified by type, dominant energy source, location, and regional affiliation (coastal and continental Croatia), and differences in energy consumption, costs, and emission profiles across groups will be analysed. Special attention will be paid to the spatial distribution of consumption and emissions, as well as to changes over time, to identify groups of buildings and locations with the greatest potential for energy renovation.

In the second stage, an econometric analysis of the determinants of energy consumption and CO_2 emissions will be conducted using a dynamic specification of a panel model with Mundlak correction, that is, a correlated random effects/within-between random effects approach. This model was selected because it matches the data structure, in which the same public buildings are observed over several years, while enabling estimation of the effects of both time-varying and time-invariant building characteristics (Mundlak, 1978; Schunck, 2013; Bell and Jones, 2015). The basic logic of the Mundlak approach is that, alongside time-varying regressors, their average values by panel unit are included in the model, thereby separating within effects, meaning changes within the same building over time, from between effects, which reflect structural differences among buildings exposed over the long term to different levels of the observed variables (Mundlak, 1978; Schunck, 2013). This approach is particularly suitable here as it allows retention of variables such as building type, dominant energy source, and regional affiliation, which the standard fixed-effects model cannot directly estimate, while also mitigating the problem of correlation between unobserved building characteristics and the explanatory variables (Bell and Jones, 2015; Wooldridge, 2020). Including the lagged dependent variable is also important, as energy consumption and CO_2 emissions typically show inertia and persistence, so the current level of these indicators depends to some extent on their previous value. At the same time, it should be noted

that using a dynamic model with fixed effects in short panels is associated with the problem of Nickell bias, that is, bias in the estimate of the coefficient on the lagged dependent variable when the number of time periods is limited (Nickell, 1981). For this reason, the selected specification is considered an interpretatively suitable empirical framework for separating effects within individual buildings and between buildings, with caution in interpreting dynamic estimates.

In the panel analysis, two models with different dependent variables will be estimated. In the first model, the dependent variable will be the logarithm of the total energy consumption of an individual building, while in the second model the dependent variable will be the logarithm of total CO_2 emissions arising from energy use in an individual building. The independent variables in both models will be the same. These will include the lagged value of the corresponding dependent variable, the logarithm of gross domestic product per capita as an indicator of the economic environment, the logarithm of county population density as an indicator of the spatial context, a climatic indicator of heating needs based on temperature deviation from 18 °C, and the logarithm of the floor area expressed in square metres. In accordance with the selected methodology, the models will also include the average values of selected time-varying variables for each building during the observed period, to distinguish the effects of changes within the same building from structural heterogeneity among buildings. In addition to these variables, both models will contain structural indicators of building type, dominant energy source and region, as well as year effects to control for common temporal influences. Office buildings, electricity and coastal Croatia will be taken as the reference categories.

The variables are not included arbitrarily, but cover the main groups of determinants of energy consumption and CO_2 emissions from buildings: economic factors, climatic conditions, physical characteristics of the building, type of energy source used, and the broader spatial and social context. The Intergovernmental Panel on Climate Change (IPCC), in the chapter on buildings, states that energy demand and emissions in buildings are linked to income, floor area, climate, building typology and broader socio-spatial patterns of space use (Intergovernmental Panel On Climate Change (Ipcc), 2023).

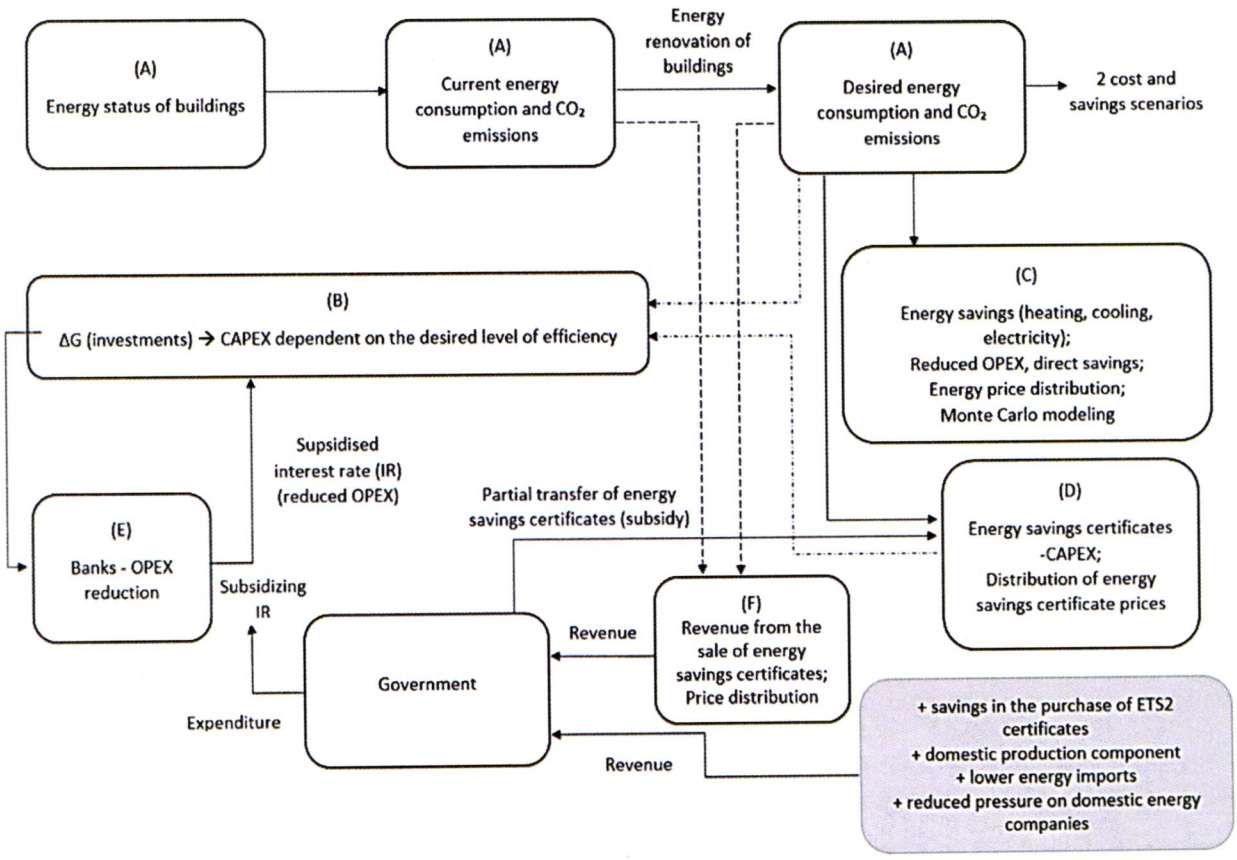
The expected direction of the relationship is defined in accordance with theoretical assumptions and previous research. A positive sign is expected for the lagged dependent variable in both models, because higher energy consumption in the previous year, or a higher level of CO_2 emissions in the previous year, indicates a higher current value of the same phenomenon. A positive relationship is also expected for floor area, as larger buildings generally require more heating, cooling, lighting, and system operation, which may result in higher energy consumption and higher CO_2 emissions. A positive relationship is expected for temperature indicators, under the assumption that a higher value indicates more climatically demanding heating conditions. For GDP per capita and its average value, a positive or ambiguous relationship is expected, because a higher level of economic development may be associated both with higher energy consumption and emissions and with a higher level of energy efficiency and the application of cleaner technologies. For population density, the expected sign is ambiguous, because higher density may simultaneously increase the intensity of space use but also reduce energy needs per unit of floor area. Compared to office buildings, hospitals, sports facilities, educational buildings, and other public buildings are expected to have higher total energy consumption and, depending on the energy source used, higher CO_2 emissions, while the expected effect for multi-family residential buildings is ambiguous or positive. For fuels, the expected sign is relative to the reference category of electricity; in the energy consumption model, it can theoretically be expected that gas, fuel oil and other more heat-intensive energy sources will be associated with higher total consumption, while in the CO_2 emissions model it is expected that energy sources with higher emission factors will be associated with higher emissions. For continental Croatia, a positive coefficient is expected in relation to coastal Croatia due to more pronounced heating needs. Year effects do not have a predefined sign because they serve to control for common temporal shocks, such as changes in energy prices, regulation, emission factors or general efficiency trends.

The testing method will be based on estimating the model coefficients and their statistical significance. Individual effects will be tested using standard coefficient significance tests, while the joint effects of selected groups of variables will be assessed using the Wald test. The Wald test will be applied not only to justify the Mundlak correction, but also to verify the joint significance of groups of dummy variables, such as building type, fuel type, and year effects (Wooldridge, 2020). In this way, it will be possible to determine whether these groups of variables contribute to explaining overall energy consumption, rather than only at the level of individual coefficients. The final interpretation of the results will focus on distinguishing changes arising from movements within the same building over time from structural heterogeneity among buildings, which is the main analytical advantage of the selected methodology.

The empirical research in the final part of the doctoral dissertation will be based on quantitative and econometric analysis of actual energy consumption and corresponding CO_2 emissions in the public building stock of the Republic of Croatia, with particular emphasis on stochastic modelling and empirically grounded assessment of uncertainty. The starting point will be an extensive dataset on actual energy consumption, energy sources, costs, and emission characteristics of the observed buildings, which will be used to determine the existing energy status of the buildings

and estimate the empirical distributions of key model variables. The input distributions for the stochastic model will be constructed from the ISGE database for variables related to actual energy consumption, energy costs, energy sources, and CO_2 emissions, while renovation costs, energy price assumptions, certificate prices, and emission unit prices will be based on supplementary cost data, market information, and available regulatory or trading data. On this basis, scenarios for the desired or achievable level of energy efficiency will be developed, with investment costs, expected energy savings, and emission reductions estimated for each scenario. The research will combine econometric modelling with simulation techniques, including the Monte Carlo approach, to generate ranges of possible outcomes and test the sensitivity of the model to changes in market and regulatory conditions (Azzini, Ivano *et al.*, 2020). The stochastic approach is chosen because renovation costs, energy prices, savings levels, and certificate prices are uncertain and may vary significantly across buildings and over time. The main methodological challenges concern data completeness, estimation of empirical distributions, assumptions regarding renovation costs and achieved savings, and the volatility of energy and emission-related prices. The analysis will also examine whether revenues from energy savings and the effects of subsidised interest rates can be incorporated into models for reducing capital and operating costs, with these effects evaluated within a probabilistic framework. The research will further assess the broader fiscal and macroeconomic effects of the proposed model to determine whether a long-term, sustainable, and fiscally acceptable framework for financing the energy renovation of public buildings can be developed.

The flow of this part of the empirical research is shown in the following diagram:



The diagram shows that the research focuses on developing a comprehensive and integrated analytical framework for evaluating the energy renovation of public buildings. Its main aim is to demonstrate how technical, environmental, financial, and fiscal aspects can be integrated into a single system that enables the assessment of both the direct and indirect effects of renovation, and provides a foundation for designing a long-term sustainable model to support the energy transition in the building sector. The research plan can be outlined in several steps. First, a systematic literature review and conceptual definition of the research framework will be conducted. In this phase, a search of the Scopus database and bibliometric analysis of the literature have already been completed to identify the key thematic groups relevant to the dissertation, forming the theoretical basis for the empirical part of the dissertation. Next, ISGE data and supplementary variables will be collected, cleaned, harmonised, and prepared for panel analysis. The third step involves descriptive and econometric data processing and interpretation of the results. In the fourth step, renovation scenarios will be developed and evaluated based on bills of quantities and estimated effects. In the final step, the

results will be integrated into a proposal for a market-based and fiscally sustainable model for the energy renovation of public buildings, with emphasis on its applicability in the Croatian context and its potential transferability to other institutionally comparable settings.

Following approval of this proposal, the researcher will begin drafting the dissertation. The dissertation is expected to be completed in approximately 15 months, by July 2027.

Work package	Estimated time
Data analysis	4 months
Design, refinement and development of the research	2 months
Pilot research	1 month
Preparation and editing of the dissertation	4 months
Finalisation of the dissertation, preparation for the defence and submission	4 months
Total duration	15 months (approximately)

3.6. Expected scientific contribution of the proposed research
(suggested length: 500 characters with spaces)

Empirical contribution: The dissertation analyses actual energy consumption and CO_2 emissions for a large sample of public buildings in the Republic of Croatia, using building-level longitudinal data rather than aggregated indicators. This provides an empirically grounded basis for examining the heterogeneity of the public building stock and identifying the economic, structural, spatial, and climatic determinants of its energy and emission performance.

Methodological contribution: The dissertation combines panel analysis of the determinants of energy consumption and CO_2 emissions with scenario-based and stochastic valuation of the costs and benefits of energy renovation, establishing a methodological framework for the simultaneous assessment of energy, environmental, financial, and fiscal effects of public building renovation under uncertainty.

Analytical contribution: The dissertation develops an integrated framework for assessing the energy renovation of public buildings, connecting energy efficiency, emission-related effects, financial sustainability, and fiscal implications within a single investment logic. Energy and CO_2 savings are not treated as only technical outcomes of renovation, but also as potential financial flows that can support the design of market based financing mechanism.

Theoretical contribution: The research contributes to the literature by linking areas that are most often analysed separately, namely the energy performance of buildings, the economic valuation of renovation, and models for financing the energy transition.

Applied contribution: The results can serve as an analytical basis for designing market-based and financially sustainable models for financing the energy renovation of public buildings.

3.7. References
(no more than 30 references)

Afshari, A. and Friedrich, L. (2016) 'A proposal to introduce tradable energy savings certificates in the emirate of Abu Dhabi', *Renewable and Sustainable Energy Reviews*, 55, pp. 1342–1351. Available at: https://doi.org/10.1016/j.rser.2015.05.086.

Ahmadi, M. *et al.* (2020) 'Development of an ESCO Risk Assessment Model as a Decision-Making Tool for the Energy Savings Certificates Market Regulator: A Case Study', *Applied Sciences*, 10(7), p. 2552. Available at: https://doi.org/10.3390/app10072552.

Allcott, H. and Greenstone, M. (2012) 'Is There an Energy Efficiency Gap', w17766. Available at: https://doi.org/https://doi.org/10.3386/w17766.

Attia, S. (2022) 'Data on residential nearly Zero Energy Buildings (nZEB) design in Eastern Europe', *Data in Brief*, 43, p. 108419. Available at: https://doi.org/10.1016/j.dib.2022.108419.

Azzini, Ivano *et al.* (2020) *Uncertainty and sensitivity analysis for policy decision making: an introductory guide*. Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2760/922129 (Accessed: 19 May 2026).

Bell, A. and Jones, K. (2015) 'Explaining Fixed Effects: Random Effects Modeling of Time-Series Cross-Sectional and Panel Data', *Political Science Research and Methods*, 3(1), pp. 133–153. Available at: https://doi.org/10.1017/psrm.2014.7.

Bertoldi, P. *et al.* (2010) 'Energy supplier obligations and white certificate schemes: Comparative analysis of experiences in the European Union', *Energy Policy*, 38(3), pp. 1455–1469. Available at: https://doi.org/10.1016/j.enpol.2009.11.027.

Coase, R.H. (2013) 'The Problem of Social Cost', *The Journal of Law & Economics*, 56(4), pp. 837–877. Available at: https://doi.org/10.1086/674872.
Costantini, V., Crespi, F. and Paglialunga, E. (2018) 'The employment impact of private and public actions for energy efficiency: Evidence from European industries', *Energy Policy*, 119, pp. 250–267. Available at: https://doi.org/10.1016/j.enpol.2018.04.035.
Dall'O', G. and Sarto, L. (2013) 'Potential and limits to improve energy efficiency in space heating in existing school buildings in northern Italy', *Energy and Buildings*, 67, pp. 298–308. Available at: https://doi.org/10.1016/j.enbuild.2013.08.001.
El-Darwish, I. and Gomaa, M. (2017) 'Retrofitting strategy for building envelopes to achieve energy efficiency', *Alexandria Engineering Journal*, 56(4), pp. 579–589. Available at: https://doi.org/10.1016/j.aej.2017.05.011.
Faggianelli, G.A., Mora, L. and Merheb, R. (2017) 'Uncertainty quantification for Energy Savings Performance Contracting: Application to an office building', *Energy and Buildings*, 152, pp. 61–72. Available at: https://doi.org/10.1016/j.enbuild.2017.07.022.
Fang, W.S., Miller, S.M. and Yeh, C.-C. (2012) 'The effect of ESCOs on energy use', *Energy Policy*, 51, pp. 558–568. Available at: https://doi.org/10.1016/j.enpol.2012.08.068.
Fawcett, T., Rosenow, J. and Bertoldi, P. (2019) 'Energy efficiency obligation schemes: their future in the EU', *Energy Efficiency*, 12(1), pp. 57–71. Available at: https://doi.org/10.1007/s12053-018-9657-1.
Fiaschi, D., Bandinelli, R. and Conti, S. (2012) 'A case study for energy issues of public buildings and utilities in a small municipality: Investigation of possible improvements and integration with renewables', *Applied Energy*, 97, pp. 101–114. Available at: https://doi.org/10.1016/j.apenergy.2012.03.008.
Gholamzadehmir, M. *et al.* (2025) 'Increasing the Market Value of Buildings Through Energy Retrofitting: A Comparison of Actual Retrofit Costs and Perceived Values', *Buildings*, 15(3), p. 376. Available at: https://doi.org/10.3390/buildings15030376.
Giraudet, L.-G. and Finon, D. (2015) 'European experiences with white certificate obligations: A critical review of existing evaluations', *Economics of Energy & Environmental Policy*, 4. Available at: https://doi.org/10.5547/2160-5890.4.1.lgir.
Hirvonen, J. *et al.* (2022) 'Socio-economic impacts of large-scale deep energy retrofits in Finnish apartment buildings', *Journal of Cleaner Production*, 368, p. 133187. Available at: https://doi.org/10.1016/j.jclepro.2022.133187.
Intergovernmental Panel On Climate Change (Ipcc) (ed.) (2023) 'Buildings', *Climate Change 2022 - Mitigation of Climate Change*. 1st edn. Cambridge University Press, pp. 953–1048. Available at: https://doi.org/10.1017/9781009157926.011.
Keliauskaite, U. *et al.* (2025) 'Financing European Union's buildings' decarbonisation strategy', *Energy Policy*, 198, p. 114437. Available at: https://doi.org/10.1016/j.enpol.2024.114437.
Li, Y., Qiu, Y. and Wang, Y.D. (2014) 'Explaining the contract terms of energy performance contracting in China: The importance of effective financing', *Energy Economics*, 45, pp. 401–411. Available at: https://doi.org/10.1016/j.eneco.2014.08.009.
Ma, H. *et al.* (2017) 'Analysis of typical public building energy consumption in northern China', *Energy and Buildings*, 136, pp. 139–150. Available at: https://doi.org/10.1016/j.enbuild.2016.11.037.
Maduta, C. *et al.* (2023) 'Towards climate neutrality within the European Union: Assessment of the Energy Performance of Buildings Directive implementation in Member States', *Energy and Buildings*, 301, p. 113716. Available at: https://doi.org/10.1016/j.enbuild.2023.113716.
Mikulić, D., Bakarić, I.R. and Slijepčević, S. (2016) 'The economic impact of energy saving retrofits of residential and public buildings in Croatia', *Energy Policy*, 96, pp. 630–644. Available at: https://doi.org/10.1016/j.enpol.2016.06.040.
Mikulić, D. and Keček, D. (2021) 'Investments in Croatian RES Plants and Energy Efficient Building Retrofits: Substitutes or Complements?', *Energies*, 15(1), p. 2. Available at: https://doi.org/10.3390/en15010002.
Mundlak, Y. (1978) 'On the Pooling of Time Series and Cross Section Data', *Econometrica*, 46(1), pp. 69–85. Available at: https://doi.org/10.2307/1913646.
Newsham, G.R. (2019) 'Measurement and verification of energy conservation measures using whole-building electricity data from four identical office towers', *Applied Energy*, 255, p. 113882. Available at: https://doi.org/10.1016/j.apenergy.2019.113882.
Nickell, S. (1981) 'Biases in Dynamic Models with Fixed Effects', *Econometrica*, 49(6), pp. 1417–1426. Available at: https://doi.org/10.2307/1911408.
Ouedraogo, B.I., Levermore, G.J. and Parkinson, J.B. (2012) 'Future energy demand for public buildings in the context of climate change for Burkina Faso', *Building and Environment*, 49, pp. 270–282. Available at: https://doi.org/10.1016/j.buildenv.2011.10.003.
Pigou, A.C. (1920) 'The Economics of Welfare (4th ed.)'. Available at: https://doi.org/https://oll.libertyfund.org/titles/pigou-the-economics-of-welfare.

Schunck, R. (2013) 'Within and between Estimates in Random-Effects Models: Advantages and Drawbacks of Correlated Random Effects and Hybrid Models', *The Stata Journal*, 13(1), pp. 65–76. Available at: https://doi.org/10.1177/1536867X1301300105.
Shang, T. *et al.* (2017) 'A review of energy performance contracting business models: Status and recommendation', *Sustainable Cities and Society*, 34, pp. 203–210. Available at: https://doi.org/10.1016/j.scs.2017.06.018.
Trovato, M.R., Nocera, F. and Giuffrida, S. (2020) 'Life-Cycle Assessment and Monetary Measurements for the Carbon Footprint Reduction of Public Buildings', *Sustainability*, 12(8), p. 3460. Available at: https://doi.org/10.3390/su12083460.
Tuominen, P., Forsström, J. and Honkatukia, J. (2013) 'Economic effects of energy efficiency improvements in the Finnish building stock', *Energy Policy*, 52, pp. 181–189. Available at: https://doi.org/10.1016/j.enpol.2012.10.012.
Williamson, O.E. (1981) 'The Economics of Organization: The Transaction Cost Approach', *American Journal of Sociology*, 87(3), pp. 548–577.
Wooldridge, J. (2020) 'Correlated random effects methods for panel data models with heterogeneous time effects', *London Stata Conference 2020*. Stata Users Group. Available at: http://fmwww.bc.edu/repec/usug2020/Wooldridge_u20.pdf (Accessed: 17 April 2026).
Zekić-Sušac, M., Has, A. and Knežević, M. (2021) 'Predicting energy cost of public buildings by artificial neural networks, CART, and random forest', *Neurocomputing*, 439, pp. 223–233. Available at: https://doi.org/10.1016/j.neucom.2020.01.124.
Zhang, Yuhang *et al.* (2022) 'Effect of physical, environmental, and social factors on prediction of building energy consumption for public buildings based on real-world big data', *Energy*, 261, p. 125286. Available at: https://doi.org/10.1016/j.energy.2022.125286.

3.8. Total cost estimate of the proposed research
(in HRK)

3.9. Proposed research funding sources

Type of funding	Project name	Project leader	Signature
National funding			
International funding			
Other project types			
Self-funding			

3.10. Ethics committee meeting at which the research proposal was approved
(if applicable)

CONSENT OF THE PROPOSED SUPERVISOR WITH TOPIC APPPROVAL REQUEST

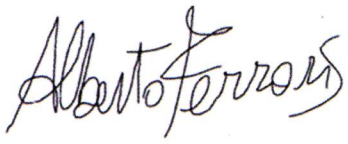
I hereby declare that I agree with the proposed PhD thesis topic.

Signature
Prof. Ivana Tomas Žiković, PhD

Ivana Tomas Žiković

Signature

Prof. Alberto Ferraris, PhD



STATEMENT

I declare that this doctoral thesis has been registered under the Cotutelle Agreement between the University of Rijeka and the University of Turin, and that it will result in the awarding of a double doctorate at both universities. The thesis will be written in English.

Signature
Lorena Dabac

Rijeka, 22/05/2026

Odgovori i objašnjenja na sugestije povjerenstva:

- Sažetak je preoblikovan tako da više nije deskriptivan prikaz dokumenata i inicijativa. Naglasak je stavljen na energetsku obnovu javnih zgrada kao problem potrošnje energije, emisija CO_2, investicijskih troškova, financijske održivosti i oblikovanja tržišno utemeljenog modela obnove. U sažetku su sada istaknuti predmet istraživanja, korišteni podaci, vremenski i prostorni obuhvat, metodološki pristup te očekivani znanstveni doprinos.
- Vremensko razdoblje istraživanja je precizirano: analiza temelji na podacima za razdoblje od 2020. do 2025. godine.
- U novoj verziji prijave iz glavnih ciljeva disertacije definirani su posebni ciljevi istraživanja. Ciljevi sada obuhvaćaju analizu obrazaca potrošnje energije i emisija CO_2, procjenu utjecaja strukturnih, prostornih i ekonomskih čimbenika, oblikovanje scenarija integrirane i dubinske obnove, ispitivanje financijske održivosti ulaganja te procjenu uvjeta za tržišno utemeljen i fiskalno prihvatljiv model financiranja. Hipoteze su potom formulirane tako da se izravno nadovezuju na navedene ciljeve.
- Pregled literature je proširen i usmjeren na ključna područja teme: energetsku učinkovitost, dekarbonizaciju zgrada, determinante potrošnje, ESCO/EPC modele, certifikate ušteda i tržišne instrumente. U novoj verziji pregled literature nije organiziran kao prikaz pojedinačnih autora, nego postupno vodi prema istraživačkoj praznini. Najprije se obrađuju regulatorni i financijski izazovi dekarbonizacije zgrada, zatim energetski jaz učinkovitosti i tržišni neuspjesi, pa determinante potrošnje energije, makroekonomski učinci obnove, institucionalni i financijski modeli provedbe te monetizacija energetskih i emisijskih ušteda. Na kraju pregleda literature istaknuto je da postojeća istraživanja uglavnom zasebno analiziraju ove cjeline, dok nedostaje integrirani okvir koji istodobno obuhvaća potrošnju, emisije, troškove obnove, tržišne poticaje i financijsku održivost.
- U dorađenoj verziji prijave dodani su izvori koji nedostaju.
- Popis literature je usklađen s tekstom prijave, a povećan je udio empirijskih znanstvenih radova koji služe za obrazloženje teme, istraživačkog problema i ciljeva istraživanja.
- Jezična i terminološka dosljednost je poboljšana tako što je prijava izrađena na engleskom jeziku, uz uporabu stručne terminologije i kratica pri prvom navođenju pojmova, npr. EPBD, nZEB, ESCO, EPC i EEOS.
- Nova verzija prijave pisana je u trećem licu.
- Hipoteze su preciznije formulirane i operacionalizirane kroz metodološki dio istraživanja. U dorađenoj verziji prijave, hipoteze su jasnije povezane s ciljevima istraživanja: H1 se odnosi na determinante potrošnje energije i emisija CO_2, H2 na učinke integrirane i dubinske obnove, a H3 na financijski učinak uključivanja energetskih i emisijskih ušteda u model obnove. Dodatno su navedene zavisne varijable, odnosno ukupna potrošnja energije i emisije CO_2, kao i nezavisne varijable: BDP po stanovniku, gustoća naseljenosti, klimatski pokazatelji, površine zgrada, tipovi zgrada, dominantni energent, regija i godišnji učinci. U tekstu su obrazloženi očekivani smjerovi odnosa među varijablama te je preciziran način testiranja kroz procjenu koeficijenata, testove njihove statističke značajnosti i Wald test za zajedničku značajnost skupina varijabli.
- Stohastički dio istraživanja dodatno je razrađen i metodološki obrazložen. U dorađenoj verziji prijave pojašnjeno je da će se model temeljiti na empirijskim distribucijama izvedenima iz stvarnih podataka, prvenstveno iz ISGE baze za potrošnju energije, troškove, energente i emisije CO_2, te iz dopunskih troškovnih, tržišnih i regulatornih podataka za troškove obnove, cijene energije, certifikate ušteda i emisijske jedinice. Obrazloženo je da je stohastički pristup, uključujući Monte Carlo simulacije temeljene na empirijski utvrđenim distribucijama varijabli i

međusobnim korelacijama, odabran zbog neizvjesnosti i varijabilnosti troškova, cijena i ušteda među zgradama i kroz vrijeme.

- Odabir Republike Hrvatske dodatno je obrazložen kao metodološki opravdana nacionalna studija slučaja. U dorađenoj verziji pojašnjeno je da istraživanje zahtijeva detaljne longitudinalne mikro podatke na razini pojedinačnih javnih zgrada, koje omogućuje ISGE baza. Budući da usporedive baze za druge države nisu bile dostupne, istraživanje nije oblikovano kao komparativna analiza, nego kao dubinska empirijska analiza stvarnog fonda javnih zgrada, s potencijalom primjene modela u institucionalno usporedivim okruženjima.