TECHNO-ECONOMIC AND ENVIRONMENTAL OPTIMIZATION OF HEAT SUPPLY SYSTEMS IN URBAN AREAS

by

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The present work deals with an optimization model for selection of optimal heating structure in urban areas also considering the environmental aspects. The optimization model was established in order to facilitate the decision making during selection phase of heat sources locations and defining the boundaries of their action at the pre-design phase of heat supply schemes development of settlements. Within the model is performed comparative analysis between ten heating systems, whereas as leading criteria in the comparison procedure are considered heat load density per unit of area, techno-economic aspects, and environmental impact. The optimization result actually defines the optimal heating system type in regard of the heat load density per unit area. The model provides possibility in defining standard values of heat density indicators, according to which can be assessed the economic feasibility of implementing district heating system for the selected urban area. The less value of heat density in the system, the higher specific costs for generation, distribution, and transmission of heat energy. Furthermore, the model is applied and verified for the local urban, infrastructural, technical and environmental conditions of the city of Skopje. The process of determination of optimal heating structure has holistic approach, where, beside techno-economic aspects and feasibility, the environmental aspect of different heating systems is considered as a major factor (threat) in air pollution.

Key words: *energy efficiency, heating, building, sustainability, air pollution*

Introduction

Every year, over 40% of the total energy consumed in Europe is used for the generation of heat for either domestic or industrial purposes, whereas the cooling demand is growing exponentially [1, 2].

Buildings within different sectors (residential, commercial, public, *etc.*) are major consumers of energy throughout their lifecycle [3]. This trend is also linked to climate change and the global warming issue. In industry, 70.6% of energy consumption (193.6 Mtoe) was used for space and industrial process heating, 26.7% (73.3 Mtoe) for lighting and electrical processes such as machine motors, and 2.7% (7.2 Mtoe) for cooling [1]. To achieve the decarbonization objectives, buildings sector must be decarbonized. This entails renovating the existing building stock, along with intensified efforts in energy efficiency and renewable energy, supported by decarbonized electricity and district heating [2].

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Due to the limited energy resources, their price and the significant environmental impact of the energy conversion processes, the efficient use of energy is a matter of general interest in the world. Better energy efficiency helps achieving cleaner environment, higher living standard, more reliable energy supply and more competitive businesses. An important step towards the implementation of well organized set of measures to enhance energy efficiency in buildings is determination of the state-of-the-art of energy efficiency, represented through specific energy indicators [4]. The aim of the work [5] was to analyze and explore the most suitable energy policy instruments for energy efficiency improvement in particular country (Serbia). The analysis has been carried out with a focus on energy indicators for the country, compared to the EU27, encompassing a period of 22 years and directed towards the consideration of amendments that need to be made in the National Energy Efficiency Policy.

The main objective of the study presented in [6] was to evaluate the thermal properties of existing residential buildings built in industrial manner in city of Novi Sad, Serbia, from 1960 to 1990, based on building typology. Three building types were subject of analysis, each of them with characteristic façade, with thermal performances divided into periods according to the development of domestic thermal protection building codes.

In some parts of Europe, up to three quarters of the outdoor fine particulate matter pollution is attributable to household heating with solid fuels (including coal and biomass). The Commission has initiated infringement procedures on ambient air quality against several member states, referring two cases regarding persistently high levels of fine particulate matter to the European Court of Justice in 2015 [7]. The Commission warns about the negative impact on air quality from the use of coal (lignite) and boilers and stoves with poor emission standards for heating, as healthier solutions are available, easily accessible and more efficient and cheaper in the long run [7].

The research for optimization of urban centralized heat supplying systems, beside saving financial resources, reducing heat energy consumption and improving the enterprise benefit, is an important tool to realize safe and reliable heating. Therefore, the optimal planning of heat supply network in order to transform central heating systems (CHS), with the use of advanced technologies, has significant role in the frame of urban planning, related to overall social benefit [8].

For a district heating system, the selection of the heat source makes significant impact on the energy efficiency and the pollutant emissions. There is developed analytic hierarchy process (AHP) and the preference ranking organization method for enrichment evaluation (PROMETHEE), a multiple-attribute decision-making scheme for the heat source selection of district heating systems, providing qualitative and quantitative attributions easy to be treated together in the decision-making process [9].

Current and future interest is expanding in the use of district heating as a way to provide flexibility to power systems, by storing energy from the electric power grid as heat, which reflects a more general increased interest in the electrification of the heating sector. Lund and Mathiesen [10], in their comprehensive study that targeted 100% renewable energy systems in Denmark until the year 2050, underlined the importance of the following measures that are related to the expansion and advancement of district energy systems:

- replace individual house heating by district heating combined heat and power (CHP),
- supply 15% of individual and district heating demand by solar thermal power,
- increase electricity production from industrial CHP by 20%, and
- introduce 450 MW large heat pumps in combination with existing CHP systems.

Lund *et al.* [11] further advocated the benefits of district energy systems and presented the characteristics of fourth-generation district heating. The centrality of smart thermal grids for district heating and cooling are emphasized to obtain smart energy systems.

In Denmark, development and implementation of district heating gathered speed in the aftermath of the two international oil crises in the 1970s [12]. As a result of comprehensive national programmes and analyzes of different alternatives for supply of heat and power, it was decided to focus on expansion of the fuel efficient combined heat and power systems. In this success, district energy has already achieved an extremely important role in the energy sector (including its potential role for energy storage capacity), in which the district-heating market penetration has increased substantially.

The scope of the study [13] is to compare the heating systems most commonly used in the Greek residential sector, by using the equipment's efficiency and the lifecycle cost as criteria. As the majority of buildings were constructed prior to the introduction of mandatory thermal insulation in 1979, space heating is the major cause of energy consumption in residential buildings. The study aims to facilitate this selection by describing and comparing different heating systems for the statistically representative three floor, multi-family apartment building, built according to the latest Greek energy efficiency regulation. A sensitivity analysis has been carried out for the four climatic zones in which Greece is subdivided with climatic conditions similar to those found throughout the Mediterranean. The systems' overall performance is evaluated based on their total lifecycle cost as well as the environmental burden associated with the fuel used.

The present work deals with comparative techno-economic analysis of different heating systems in urban areas, *i. e.* current and potential (possible) ways of heating in city of Skopje, taking in the foreground their impact on the environment. The analysis was conducted considering several important aspects: technical feasibility (availability), level of necessary investments, operating and maintenance costs, comprehensive techno-economic analysis, and environmental impact. The main goal of the study is to obtain relevant information and indicators, aiming to facilitate the decision making during selection phase of heat sources locations and defining the boundaries of their action at the pre-design phase of heat supply schemes development of settlements. The model for determining the techno-economic optimal type of heating is based on the segmentation of the considered area of the city to model regions with defined dimensions.

Background analysis

Almost half of the buildings in EU have individual boilers installed before 1992, with efficiency of 60% or less. An 22% of individual gas boilers, 34% of direct electric heaters, 47% of oil boilers, and 58% of coal boilers are older than their technical lifetime. The importance of the heating and cooling sector is underlined in the EU energy policy initiatives [7]. This emphasize the role of technologies based on RES combined with high-efficiency energy technologies, to meet the heating and cooling demand in Europe more sustainably in the future. In this context, it is essential to identify the current and future heating and cooling demand and the technologies employed in the domestic, commercial and industrial sectors of the EU.

District heating systems basically make use of heat produced in central locations and distribute it through pipelines to a large number of end users. In that way, heat, that has very low value in one place, *e. g.* industrial surplus heat, can be transformed to high-value thermal energy, in places where there is a high demand for heat, such as large urban communities. Individual heating solutions only allow one specific type of fuel, *e. g.* coal, oil or natural gas. For the end user, this means that the heating bill is fully financially exposed to price fluctuations of a specific fuel. With district heating, it is possible to take advantage of the free market forces driving price changes on different types of fuel. District heating also makes it possible to meet other of society's preferences and political goals, *e. g.* independence from import of fuel and meeting CO_2 targets. In short, it is much simpler to change fuel from, *e. g.* natural gas at one central place than having to change boilers in thousands of individual houses. With large district heating systems, it is possible to make that change almost from day-to-day [14].

In order to verify the results, the optimization model is rearranged according the conditions for the city of Skopje. This tool further provides strong guidelines for choosing the optimal way of heating in separate parts of the city, which is a city with complex socio-demographic, spatial, economic, and ecological area. The density of the population, infrastructure, economic activities and other parameters vary significantly between individual municipalities, but also between parts located within the municipalities. It is performed comparative analysis of the techno-economic and environmental aspects of a ten heating types has been realized, which are usually present or available in the city, taking into account their technical, financial, economic, and environmental parameters. In the input parameters are used the results from the survey which had the aim to obtain data on the ways of heating in the residential sector conducted in the city of Skopje in 2013 and covering 166335 households. The main results from the survey show that in the more urban municipalities the central hot-water heating system is predominant, but the use of fire-wood for heating has the biggest share with 40.4% on the city level [12, 13].

Methodology

The module for calculating energy consumption includes determination/calculation of the required heat to meet different energy needs. Input parameters of this module are related to the urban and demographic characteristics of a particular area (area, number of inhabitants, number of dwellings, number and type of objects, type of building, *etc.*). It is important to emphasize that the input parameters of this model can be adopted for the whole area of the considered city/urban area, but more reliable results will be obtained if the considered urban area is divided into parts with identical urban settlement.

The model for determining the techno-economic optimal type of heating is based on the segmentation of the considered area of the city to model regions with defined dimensions.

Defining the boundaries of the observed urban area is the initial step in the process of optimization the structure for the energy supply, fig. 1 [15, 16]. Normally the boundaries are set in accordance with the official territorial segmentation. Also, in the process of segmentation it should be considered that in most urban areas there is permanent spatial and demographic expansion. Usually, the segmentation is not homogenous from the point of view of energy needs. There are areas with different density of buildings distribution, different size of buildings, and different energy performances. Since these are the deterministic characteristics of certain region in the process for selecting optimal heating system, it is necessary to divide the city urban area into homogeneous city quarters with residential and common facilities called constriction surfaces. It should be emphasized that reliability of the selected optimal heating system for the city square strongly depends on the division strategy of the urban area.

Knowing that there is considerable number of different real building areas and the requirement for determination of the heating energy consumption of each of these areas, there is a need to introduce a universal model region that would reflect the characteristics of each real situation.

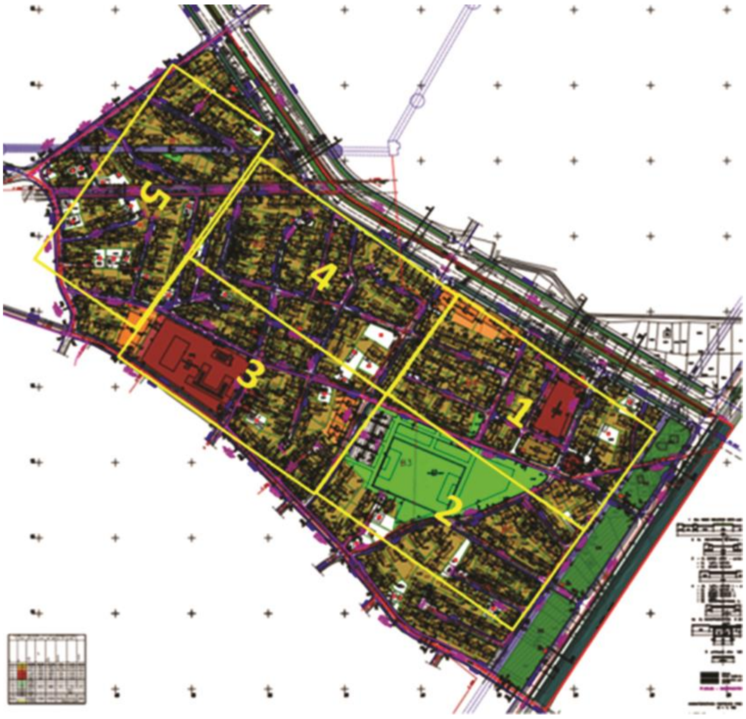

Figure 1. An example of segmentation of a part of city area for modeling purposes [15, 16]

When preparing the model, a pattern flat with heating surface of 60 m^2 has been adopted, which is in accordance with the actual market offer of flats in new residential areas in recent years [15, 16]. This is, also, in correspondence with the purchasing power and desires of customers, given that the statistical average area of apartments that have been bought/sold lately is about 60 m^2. The current average residential area in city of Skopje urban area is 69 m^2 [17]. If we subtract from this area the non-heated part (balconies, corridors, *etc.*), it can be concluded that the adopted heating surface in the model match the real situation. Construction physics, *i. e.* the materials used and the thermal insulation of the residential building under consideration comply with the regulations for energy efficiency of buildings [15, 16].

By introducing model region, it is possible to conduct research on this model (for example, pipelines structure and the costs of their construction, which affects the costs of energy supply) and then to apply it into each of the segmented urban areas – city quarters. This provides possibility the results obtained from the model region research, with few or no corrections, to be applied into decision making process for district energy supply to other cities or urban areas.

In order this model to be applicable in any urban environment, settlement, municipality, city, *etc.*, a relatively small model region with dimensions of 315 m ×160 m was adopted. In order to cover different cases of possible arrangement of objects on a conditional building area and to determine the energy and economic characteristics, for the given analysis, the building areas were adopted with 4, 8, 16, 32, 64, and 128 objects. Further, the city quarters, defined according to detailed urban plans (DUP), are segmented with the model region. The number of model regions depends on the size of the district area. The next step is defining the heat load density, which is obtained through counting the number of objects in individual model regions and determination of their heat demand in accordance with information on technical and infrastructure characteristics of the given region. Depending on the heat load density, the following heat loads were adopted: 10, 20, 30, 40, 50, 75, 100, and 125 MW/km^2.

In the optimization model, for each number of buildings in the model region, it is possible to express the costs of energy supply as function of the density of the heated consumer on that surface.

The modules for investment cost determination consist of a database with prices of individual components of the analyzed heating system.

The optimization model structure is composed of three parts (presented in fig. 2, according to [15]):

(1) input parameters – In this part are the values for the economic and technical parameters. Here are considered prices for boilers, efficiency of heating devices, equipment prices, energy tariffs, *etc.*,
(2) calculations – The calculations shall comprise economic, technical data, as well as the operating and exploitation costs necessary for the subsequent calculation of investment costs, and
(3) calculation results – The adopted models are applied to a certain area (municipality, city, *etc.*).

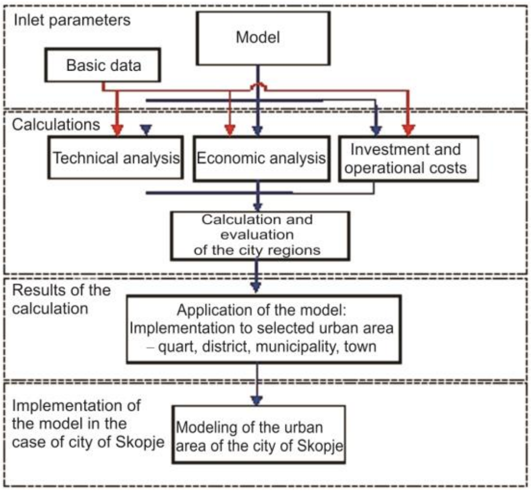

Figure 2. A general flow diagram of the model for determination of optimal heating mode, according to [15]

Within the model, for each of the analyzed types of heating the key technical, economic, operational and exploitation parameters are taken into account. At the same time, separate lots were created, divided according to technical parameters, investment parameters, economic parameters, operational-exploitation parameters and calculation of economic viability. The economic viability of individual types of heating is considered by the method of a discontinuous cash flow over a 25-year working life, after which a comparison of the NPV for each type of heating is made in relation to the NPV of the district heating system.

Case study: The city of Skopje

A pattern flat with heating surface of 60 m^2 has been adopted within the model, which, in terms of technical characteristics, is in accordance with the actual market offer in new residential areas in recent years. The construction physics, *i. e.* the materials used and the thermal insulation of the residential building under consideration comply with the regulations for energy efficiency of buildings [18, 19]. Further on, for the referent apartment, calculations are performed for deriving the heat losses and annual heat energy consumption, based on ISO 13790 [16]. According to the results of the calculations, specific values are defined in [Wm^{-2}] and [$kWhm^{-2}$ per year], which are further used in the general model matrices for calculation of heat load density and energy consumption. Also, specific installation costs (in € per m^2) are defined for each of the analyzed heating systems, derived from the total heating systems costs applied on the referent apartment model, which do not include the heat source (devices) costs. It should be noted that distribution and connection pipelines exist only in the district heating and gas pipeline system, while in the other heating systems they do not exist and the calculations are made only for the investment costs in the facilities.

Within tab. 1 is given an overview over the used heating system types in the optimization model assessment. All of the analyzed heading systems have common installation costs, calculated with 40 €/m^2, excluding the price of the heating source.

As influencing factors in the optimization process are considered: the harmful impact on the environment, meeting the necessary techno-economic criteria, achieving comfortable conditions in the living and working space, *etc.* In this regard, the existing applied, as well as the available heating methods in the conditions of the city of Skopje have been studied and the legal frameworks and applicable regulations that are relevant for the issue of supply of heating energy in urban areas have been analyzed.

In accordance with a general urban plan, the city of Skopje is divided into quarters. Within each quarter, segmentation of the area with the model regions has been carried out. Generally, each quarter in city of Skopje is defined by an appropriate DUP in the perspective, *i. e.* expected condition of the district in the future. The area of each quarter is segmented to the dimensions of the defined model region (315 m × 160 m), and the number of model regions depends on the area of the quarter being analyzed. Then the number of objects in the individual model regions is counted and their thermal load is determined according to the detailed information on the respective construction parcels defined in the DUP. This value is multiplied by the total gross surface area of that building parcel, and then multiplied by a coefficient of 0.8, in order to bring the grossly developed surface to a net built surface. In this way, the unheated area is foreseen for corridors, stairs, elevators, *etc.*, and as a result, the net heating surface required for the calculation (formation of the model characteristic of the model region) is obtained. After this operation, the model characteristic of the model region is obtained, *i. e.* the matrix for the cost-effectiveness of the heating systems.

Results and discussion

In accordance with the exposition in the previous sections, the final result of the application of the model is the output matrix representing a comparison of the NPV of the individual types of heating in relation to the NPV of the CHS, depending on the number of objects and the density of the thermal load on a defined surface. The diagrams in figs. 3 to 8 present the appearances of the final matrices used in the results summary comparing the feasibility of each of the heating systems compared with district heating in regard of the number of buildings in model regions, *i. e.* the heat load density. In the diagrams are presented values for the percentage difference between NPV for district heating and rest of the analyzed types of heating systems.

The results presented in these diagrams point out that collective residential heating with air-to-water heat pumps is justified in regions with low thermal density.

The final result of the application of the model is the output main matrix which represents a comparison of the NPV of the individual types of heating in relation to the NPV of the CHS, depending on the number of objects and the density of the thermal load on the defined surface area.

Table 1. Heating system description and specific energy price

Heating method/system	Brief description	Technical data, model inputs	Specific heat energy price [MKD per kWh]
District heating with stations in collective buildings	The supply of heat to a particular object, settlement or city is carried out by a central heat source, whereby hot water is distributed as a heat transfer medium (temperature up to 110 °C), and heating in the buildings is hot water.	Prices of pre-insulated tubes, heat exchangers, and other equipment. Additional investment costs connection to the distribution system, which amount to 50 €/kW	
Individual heating with boilers on natural gas	Using a distribution system for natural gas that will be used for hot water heating using the application of gas boilers of each apartment individually.	Prices for condensing boilers η = 92%, gas distribution pipes, gas flow meter, Connection to the gas distribution system 10 €/kW	2.7(η = 92%)
Individual heating with boilers on pellets	Using a boiler of pellets for hot water heating of each apartment individually.	Price for pellet boiler (η = 85%), central chimney 100 €/m	2.8 (η = 85%)
Heating using pellets with the boiler room in each building	Central heating stations with pellet hot water boilers (boiler room distribution heat energy to each apartment)	Specific price pellet boiler (η = 70%) and devices €/kW, rent pellet storage space €/t, maintenance and ash removal	2.8 (η = 85%)
Central heating on fire-wood boilers	Central heating stations with solid fuel-wood hot water boilers (boiler room distribution heat energy to each apartment)	Specific price pellet boiler and devices €/kW, rent wood storage space €/t, maintenance and ash removal	2.7 (13.800 kJ/kg, 450 kg/m^3, 25% moisture)
Individual heating with electrical panel heaters	Electric panel heater in each room	Price for electric panel heaters – regarding power	5.6 high/2.8 low tariff
Heating using heat pumps on a level of each flat individually	Individual heat pump air-water and fan coils	Price for heat pump, fan coils, maintenance	1.9 high/0.9 low tariff (*COP* = 3)
Heating using heat pumps with common thermal station in buildings	Central heating stations with heat pumps (air-water)	Price for heat pump, fan coils, maintenance	1.9 high/0.9 low tariff (*COP* = 3)
Heating using air conditioners with inverter to each apartment individually	Air conditioners inverter type each apartment individually	Price for air conditioners, maintenance	1.9 high/0.9 low tariff (*COP* = 3)
Heating with boilers on light oil with boiler room in each building	Central heating stations with light oil hot water boilers (boiler room distribution heat energy to each apartment)	Specific price light oil boiler and devices €/kW, oil tank €/t, maintenance and ash removal	3.5(η = 80%)

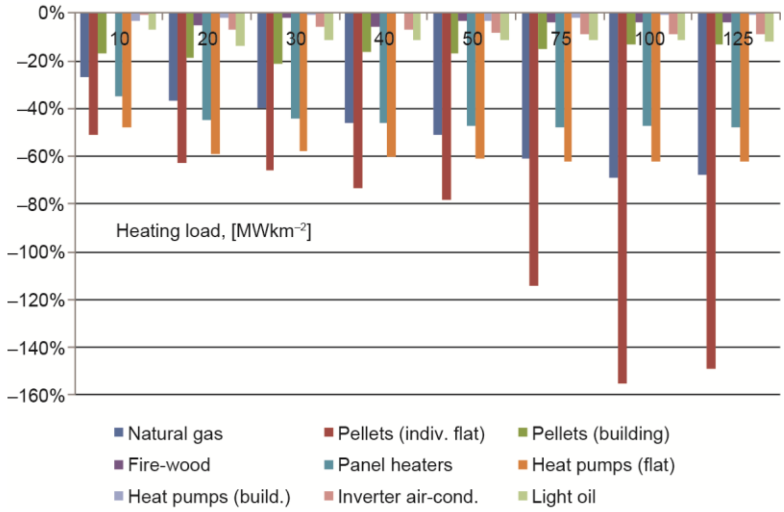

Figure 3. Difference between various heating methods related to the net actual value of the central hot-water heating system: model region with *N* = 4 objects (*for color image see journal web site*)

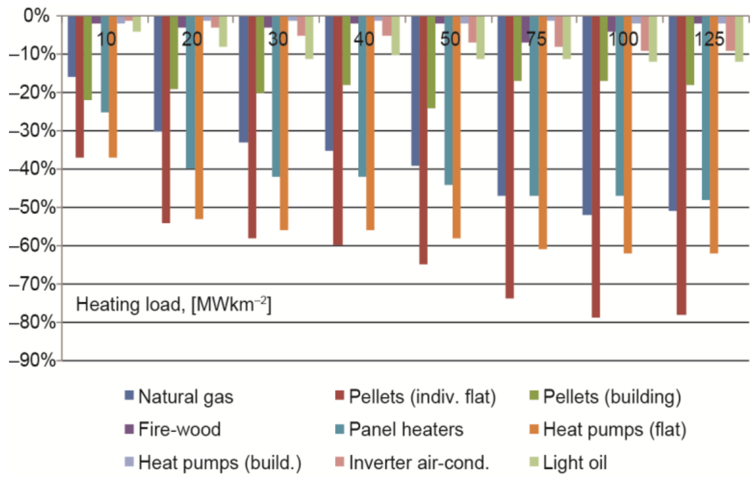

Figure 4. Difference between various heating methods related to the net actual value of the central hot-water heating system: model region with *N* = 8 objects (*for color image see journal web site*)

The CHS is mostly justified in the municipalities that represent high heat consumption, while in municipalities with low thermal energy load it is justified the use of another heating method, such as heating systems with inverter-air conditioners or heat pumps at the level of the object. In tab. 2 is presented the summary matrix of techno-economic optimum heating system. It represents the final conclusions defining the optimal heating system for the city of Skopje in regard of the heating load and number of objects.

For better graphical presentation of the results, on the segmented map of city of Skopje, given in fig. 9, every area is colored according to the optimal heating system type (color description given in legend).

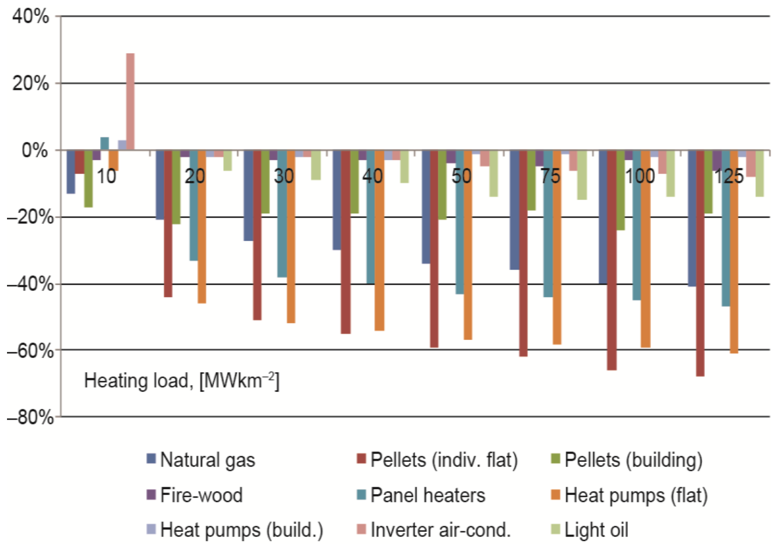

Figure 5. Difference between various heating methods related to the net actual value of the central hot-water heating system: model region with *N* = 16 objects (*for color image see journal web site*)

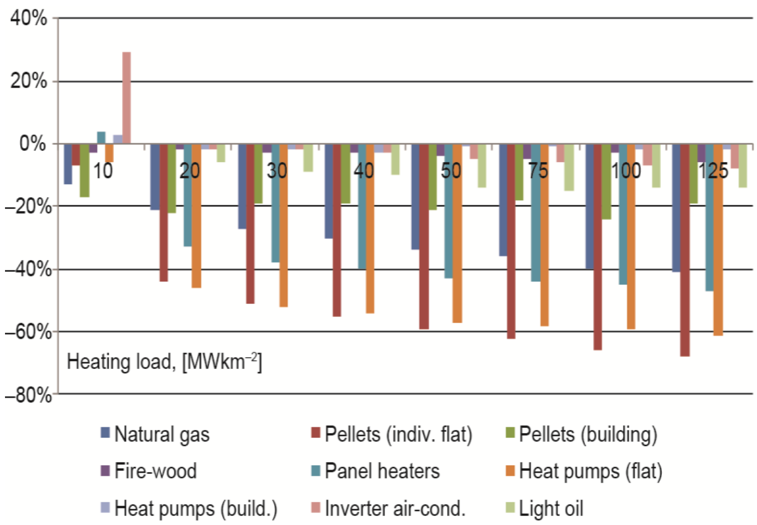

Figure 6. Difference between various heating methods related to the net actual value of the central hot-water heating system: model region with *N* = 32 objects (*for color image see journal web site*)

It can be concluded that in addition to the municipalities that are relatively less urbanized and located on the periphery, all other municipalities are characterized with a specific thermal load close to or higher than the value of 25 MW/km^2. This value in the literature is found as a limit over which the district heating system for heating in urban areas is recommended.

The results of the optimization model for the type of heating in city of Skopje have been also verified through comparison with the outputs of other studies, such as [20].

Table 2. Summary matrix of techno-economic optimum heating system

No. of buildings	Heating load, [MWkm^{-2}]							
	10	20	30	40	50	75	100	125
4	CHS	CHS	CHS	CHS	CHS	CHS	CHS	CHS
8	CHS	CHS	CHS	CHS	CHS	CHS	CHS	CHS
16	IAC	CHS	CHS	CHS	CHS	CHS	CHS	CHS
32	IAC	HP-B	CHS	CHS	CHS	CHS	CHS	CHS
64	IAC	IAC	HP-B	HP-B	CHS	CHS	CHS	CHS
128	IAC	IAC	IAC	IAC	IAC	IAC	IAC	CHS

HP-B – heat pump-building (central), IAC – inverter air conditioners (individual), CHS – central heating system

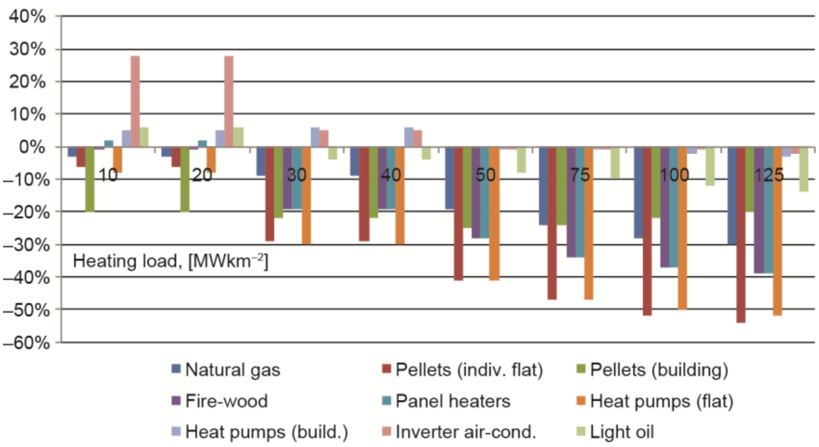

Figure 7. Difference between various heating methods related to the net actual value of the central hot-water heating system: model region with N = 64 objects (*for color image see journal web site*)

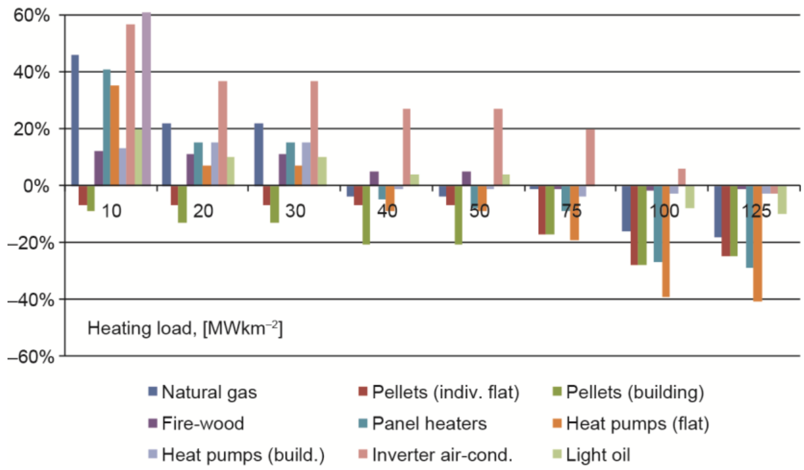

Figure 8. Difference between various heating methods related to the net actual value of the central hot-water heating system: model region with N = 128 objects (*for color image see journal web site*)

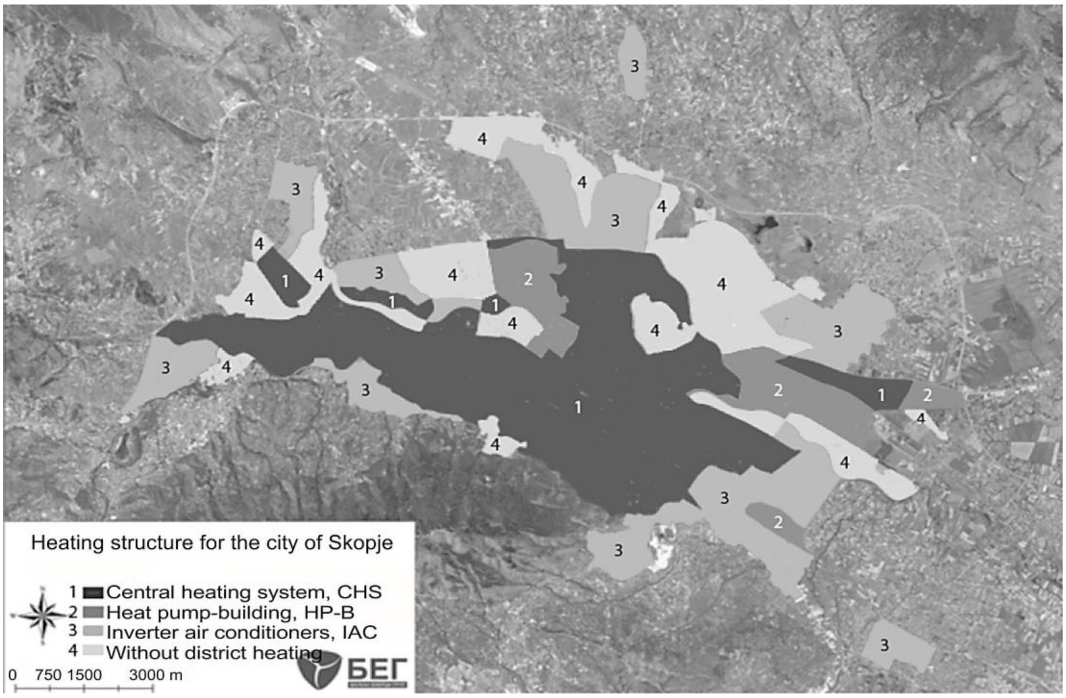

Figure 9. Techno-economic optimal heating structure for the city of Skopje (color legend, accordingly the colors in tab. 2)

Conclusions

Optimization model was developed, aiming to facilitate the decision making during selection phase of heat sources locations, as well as in defining the boundaries of their action at the predesign phase of heat supply schemes development of settlements. The model is embedded in software, which further eases its application. Within the model is performed comparative analysis between the considered heating systems, whereas as leading criteria's are considered: heat load density per unit of area, techno-economic and environmental aspects. Within the model, for each of the analyzed heating systems, the key technical, economic, operational and exploitation parameters are taken into account. In the optimization procedure it is introduced model region, on which further are conducted analyzes (as for example, pipeline structure, the costs of the construction *etc.*, which affect the costs of energy supply) and then is applied into each of the segmented urban areas – districts. In order to cover different cases of possible arrangement of objects on a conditional building area and to determine the energy and economic characteristics, building surfaces are defined with 4, 8, 16, 32, 64, and 128 objects. The economic viability of individual types of heating is considered by the method of discontinuous cash flow over a 25-year working life, after which a comparison of the NPV for each type of heating is made in relation to the NPV of the district heating system. Verification of the optimization model is performed through a case study for the city of Skopje, whereas by outcomes are defined optimal heating structures/systems for each of the districts. Obtained outcomes from this optimization model are compared with the conclusions/results from several other studies considering the same objective – optimizing heating structure in city of Skopje, whereas there is satisfactory matching between the results.

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