INNOVATIVE MECHANICAL ENGINEERING ISSN 2812-9229 (Online)
University of Niš, Faculty of Mechanical Engineering
VOL. 2, NO 1, 2023, PP. 120 - 129

Original scientific paper *

OPTIMAL ENERGY MIX FOR ASMALL-SCALE DISTRICT HEATING SYSTEM IN R. N. MACEDONIA

Elena Lazova, Igor Shesho

[1]Faculty of Mechanical Engineering, University “SS Cyril and Methodius”, Skopje, R. N. Macedonia

Abstract. *The European Union aims to be an economy with zero greenhouse gas emissions by 2050. The integration of renewable energy sources (RES) into district heating systems (DHSs) is an ongoing process. With the localization of CO_2 emissions, DHS allow easy control of the environmental impact. The integration of heating systems into a common source, i.e. connection to DHSs, enables the diversification of heat sources, which contributes to increased independency and reliability of the system's functioning, as well as optimizing the production price of heat. The purpose of this paper is to develop and simulate small district heating system with a heat demand of 7490MWh and a peak of 3470kW for the City of Ohrid, with optimal RES share in order to minimize production costs for heat. Several scenarios-systems are modeled and analyzed: solar thermal system, natural gas-fueled combined heat and power plant, photovoltaic plant, heat pumps and seasonal heat storage tank. Optimization of the considered system aims to be competitive to the existing individual heating systems.*

Key words: *Heating, Renewable Energy Sources, Energy Modeling, Optimization*

1. INTRODUCTION

In 2021, heat from district heating systems (DHSs) globally accounted for around 16EJ, an increase of 10% compared to a decade ago [1]. The global market for these systems is constantly growing, but despite this, the potential for decarbonization through the integration of renewable energy sources (RES) remains largely untapped. However, thermal energy from these systems still represents only about 8% of the total final consumption of thermal energy globally [1]. In 2021, globally almost 90% of heat is obtained from fossil fuels – dominantly coal (over 45%), especially in China, natural gas (about 40%), especially in Russia, and oil (3.5%) [1].

The European Union (EU) aims to be an economy with zero greenhouse gas emissions (climate neutrality) by 2050 [2, 3]. This goal is part of the "European Green Plan" and is in line with the EU's commitment to global climate action under the Paris

*Received: May 08, 2023 / Accepted May 22, 2023.
Corresponding author: Igor Shesho
Faculty of Mechanical Engineering, University “SS Cyril and Methodius”, Skopje, R. N. Macedonia
E-mail: igor.seso@mf.edu.mk

Agreement. The goal of reaching a climate-neutral society is both an urgent challenge and an opportunity to build a better future for all. Over the last decade, numerous strategies, regulations and policies have been implemented to encourage decarbonization, increase energy efficiency and accelerate and advance the adaptation to green energy solutions [3, 4]. In 2021, CO_2 emissions from heating systems accounted for about 3.5% of global CO_2 emissions, an increase of 3.5% compared to 2020 and 15% in 2010 [5]. According toIEA's Global Energy Review: CO_2 Emissions in 2021 [5], alignment with the net zero CO_2 emission scenario requires that the intensity of CO_2 emissions from thermal energy production be at least 20% lower by 2030 compared to 2021 and therefore significant efforts are needed to rapidly improve the energy efficiency of existing systems, using RES (such as bioenergy, solar energy, heat pumps and geothermal energy), integrating secondary sources of heat (such as waste heat from industries), and developing efficient infrastructure in areas with dense heat demand. Europe is currently leading the integration of RES in heating systems. Particularly high rates are observed in countries such as Sweden, Denmark, Austria, Estonia, Lithuania, Latvia and Iceland where more than 50% of heat is obtained from RES [1].

Most studies comparing central heating and individual heating focus primarily on analyzing the cost-effectiveness, technical performance and environmental impact of different heating technologies. Heating systems enable the localization of CO_2 emissions and harmful particles, which allows easy control of the environmental impact on environment. The integration of heating systems into a common source of heat, that is, connection to the central heat supply system, enables diversification of the heat sources, which contributes to increasing the independence and reliability in functioning of the system, as well as optimizing the production price of heat. These systems can significantly contribute to reducing environmental pollution, as well as saving energy. It is a flexible technology that can use different energy sources according to cost-effectiveness, such as fossil fuels, waste energy, and RES.

Domestic heating systems that use solar energy have the potential to be used in combination with seasonal storage, which allow energy to be stored in the summer and used in the winter. Heat pumps, especially integrated with cogeneration plants and other energy sources in DHSs, will play a major role in reducing greenhouse gas emissions in the future. Combining multiple sources of energy in one central heating system enables energy independence and the ability to adapt the system in order to meet needs in an optimal technical and economic way [6-8].

The main purpose of this paper is to demonstrate the core principles of energy modeling, whilst the software package ***nPro Energy*** is applied for energy system modeling and simulation. An energy hub will be modeled and the optimal RES share in DHSs will be determined, in order to minimize production costs for heat and electricity. By doing so, multiple systems will be combined: solar thermal systems, natural gas-fueled CHP plant, PV plant, heat pump and seasonal heat storage tank.

2. BACKGROUND

DHSs where solar energy is used as an energy source represent the largest sub-sector of large solar thermal heating systems. By the end of 2021, 299 large solar DHSs (individual capacity >350kWth, 500 m²) with a total installed capacity of 1645MWth

(~2.35 million m²) were in operation [9]. Denmark is the leader in such solar energy systems, both in terms of the number of systems and the installed area. According to [9], in addition to Denmark (125 systems) and China (41 systems), a large number of other countries (Germany, Sweden, Austria, Poland, France, Saudi Arabia, Japan, etc.) are showing increasing interest in such plants, as they offer an excellent opportunity for decarbonization of the energy sector in settlements and cities. A document [10] which brings together some of the most important experiences of solar DHS in Denmark, elaborated by Plan Energy, states that the first Danish solar DHS was established in Saltum in 1988, followed by the plants in Ry and Herlev in 1990 and Marstal in 1996. The latter was 8000 m^2 of solar collectors - at that time the world's largest. The plant in Marstal was several times extended – up to 33300 m^2 in 2018 - and seasonal heat storages were introduced, which allowed for a high solar fraction. Few benchmarking studies use the Danish district heating sector as a reference case. A paper by Dario Čulig-Tokić et al. [11] compares district heating systems in Zagreb and Aalborg; another paper by Lipeng Zhang et al. [12] provides a technical comparison of DHSs in China and Denmark.

In the study which was undertaken for DECC [13], four existing schemes were studied, among which Helsinki's system was studied as a well-established district heating and cooling network, supplying 90% of the city's heat demand and an increasing proportion of cooling demand. Even though the heat network is mainly heated by gas-fired CHP and the cooling network by absorption chillers, heat pumps and storage are integrated. In 2006, 84 MW of heat pump capacity (in 5 individual units) was integrated into the existing system, covering around 4% of the network's total heat and 33% of the total cooling. The report [13] investigates the following case studies as well: Wandsworth Riverside, London (an aquifer thermal energy storage system using heat pumps for space heating and cooling in a new development of apartments), Duindorp, Netherlands (a novel low-temperature network connected to a new development of apartments, each with its own heat pump) and Brooke Street, Derbyshire (a ground source heat pump and heat network retrofitted to small number of homes in an off-gas area).

The territory of Macedonia has excellent geographical and climatic conditions for using solar energy. Even so, until now, it has not been used to generate thermal energy through solar collectors in DHSs.

3. METHODS

The system modeling and optimization of the energy mix is conducted with a software simulation tool "nPro Energy". In the tool are integrated wide range of new innovative technologies, defined by mathematical models of the systems that are analyzed and optimized, such as systems with solar collectors, seasonal storage tanks, combined heat and power plants of natural gas, heat pumps, photovoltaic systems, etc.

The nPro tool contains two calculation modules. The first one contains demand profile generation and thermal network calculation. The second module is design optimization and operation simulation. The main connection between these two modules is the energy demand profiles at the energy hub. The demand profiles are the output of the first module and the input of the second module [14, 15]. The nPro tool processes time series with an hourly time-step, simulates and balances complex energy flows and automates the visualization of results. In Fig. 1 overview of the available technologies and energy flows in nPro is presented. In the process of defining technologies in the energy hub, the software implements a two-step design approach. In the first step, a design optimization based on linear programming defines the optimal technology selection and sizing. In the second step, the software simulates the system operation for a typical design year with more operational details [14, 15].

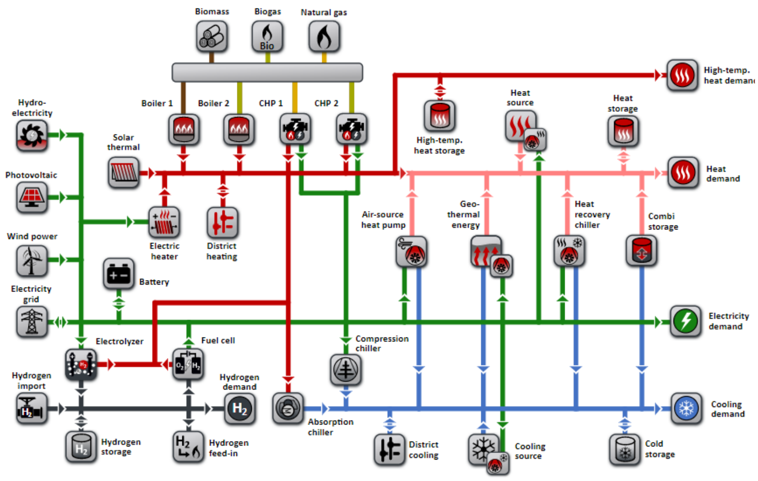

Fig. 1 Available technologies and energy flows in nPro [15]

In order to define the load profiles, several input parameters (floor area, building type, subtype, specific annual demand for space heating and DHW (kWh/m^2/year), total annual demand (MWh/year), etc.) are required by the used software tool so that the demand profiles are generated.

To define the optimal RES share in DHSs, the following steps will be applied:

- mathematical modelling of the objects under consideration, to define the hourly values of heat consumption for space heating and for the preparation of DHW,
- mathematical modelling and simulation of a combined DHS with solar collectors, seasonal storage tank, natural gas-fueled CHP plant, heat pumps, and PV plant, and
- techno-economic analysis for choosing the optimal share of energy sources.

4. Model Development

4.1 Defining load profiles for the district heating network

The climatic data and the building typology in the DH energy model are considered for the City of Ohrid – R. N. Macedonia. The district heating is foreseen to supply heat for space heating and DHW for a several public buildings located near each other on a specific area in the City of Ohrid. The heating demands are determined for each building considering the individual energy performance characteristics and defined as specific heating energy consumption kWh/m^{2}a. The demand profiles within the software are generated with an hourly time-step. In the public building are considered: schools, kindergartens, offices, hospital, student dormitory, a sports hall and a swimming pool; all of them are existing buildings. Two kindergartens have specific annual demand for space heating of 140kWh/m^2, 3kWh/m^2 for DHW and 14kWh/m^2 electricity demand. The analyzed schools with approximately 12000m^2 floor area have 98-100kWh/m^2 specific annual demand for space heating, 3-7kWh/m^2 for DHW and 14kWh/m^2 electricity demand. Several offices are included in the model with a total floor area of around 4426m^{2}requiring 77-102kWh/m^2 for space heating, 6-11kWh/m^{2}for DHW and around 47kWh/m^2 electricity demand. The other types of buildings that are included in the system are sports hall (4550m^2, 115kWh/m^2 for space heating, 37kWh/m^{2}for DHW and 50kWh/m^2 electricity demand), swimming pool (15000m^2, 102kWh/m^2 for space heating, 95kWh/m^{2}for DHW and 25kWh/m^2 electricity demand), hospital (11411m^2, 135kWh/m^2 for space heating, 45kWh/m^{2}for DHW and 125kWh/m^2 electricity demand) and a student dormitory (2972m^2, 212kWh/m^2 for space heating, 69kWh/m^{2}for DHW and 150kWh/m^2 electricity demand). The simulation results for the defined model contain data for space heating and DHW heat consumption in hourly time-steps, as well heat peak demands and total annual heating demand.

4.2 Technology selection

The energy hub is presented in Fig. 2. The considered energy hub system is composed of solar thermal collectors (system), CHP, high-temperature heat storage, heat pumps and a PV plant. The capacities are defined to cover the base heat load in design conditions.

The heat demand can be covered by heat produced by the solar thermal plant, natural gas CHP and heat pumps, while the electricity demand can be covered by the PV plant, CHP, heat pumps or from the electricity grid. By choosing these technologies, an energy mix will be conducted in order to have a reliable energy delivery.

The fuel energy costs are defined according the actual fuel prices: natural gas price 0,08eur/kWh, electricity supply price high and low tariff 0,15eur/kWh [16] and 0,12eur/kWh [17] is the electricity feed-in price.

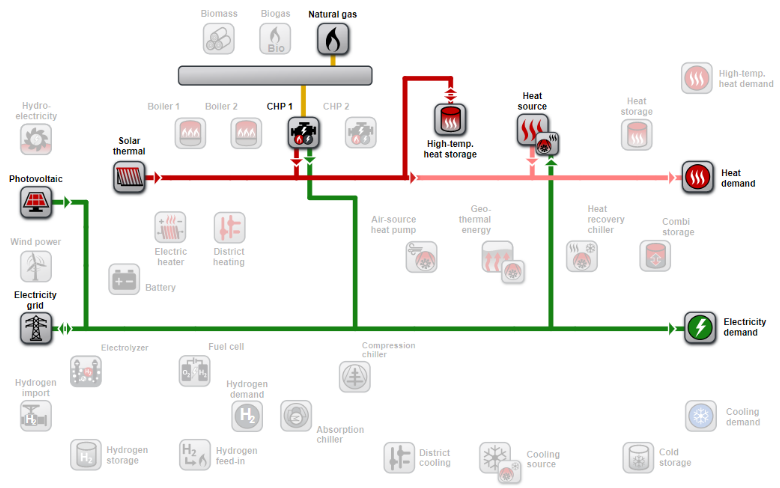

Fig. 2 Model scheme for the energy supply system

4.3 Optimal energy supply mix

In the optimization process, the optimal capacities of the systems (CHP capacity, PV module area, solar thermal area, heat pump capacity and heat storage volume) are determined. Firstly, the optimization ranges are inputted for every technology. The software pre-designs the technologies and after that, the user can change the capacity. In Fig. 3 the optimal capacities of the analyzed systems are shown. The simulation is performed using these capacities.

One can notice that the installed capacity of the solar thermal plant is 2125m^2, which is higher than the usual plants [9]. This indicates that this system will be competitive, following the latest world trends.

Technology	Optimization range	Pre-design	Full load hours/ Charging cycles	User-defined capacity
CHP 1	*unlimited*	**722 kW_{el}**	2324 h/a	722 kW_{el}
Photovoltaics	≤ 1050 kW_p / ≤ 5000 m^2	**1050 kW_p / 5000 m^2**	1266 h/a	1050 kW_p
Solar thermal	≤ 15000 m^2	**2125 m^2**	876 kWh/m^2	2125 m^2
Heat source	*unlimited*	**500 kW_{th}**	4849 h/a	500 kW_{th}
High-temp. heat storage	*unlimited*	**40407 kWh / 1740 m^3**	39 Cycles	40407 kWh

Fig. 3 Technology selection with defined capacity

5. Results and Discussion

Fig. 4 demonstrates an overview of the heat and electricity demands. The basic details of several buildings were inserted into the software, and the presented results were obtained. The annual heat requirement is 7490MWh, with a peak of 3470kW. The electricity load at the energy hub is 1710MWh, with an annual peak of 453kW.

Heat	Annual sum (MWh)	Annual peak (kW)
Heat demand of all buildings	**6740**	**3385**
Share space heating	4801	3102
Share domestic hot water	1939	505
Heat import of all buildings	**6741**	**3385**
Heat losses of heating network	749	---
Heating load at energy hub	**7490**	**3470**
Electricity	Annual sum (MWh)	Annual peak (kW)
Electricity demand of all buildings	**1617**	**430**
Share plug loads	1617	430
Share e-mobility	0	0
Electricity import of all buildings	**1618**	**430**
Pump work	92	---
Electricity load at energy hub	**1710**	**453**

Fig. 4 Heating and electricity demand at the energy hub

In Fig. 5 are presented monthly values for the heat demand where in the winter months is considered heat for both space heating and DHW and in summer months only for heating DHW.

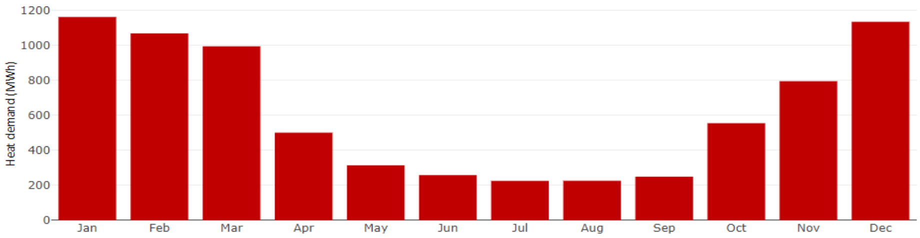

Fig. 5 Heat demand at the energy hub

It the energy hub - heating plant (DHS and electricity supply) heating energy can be provided by several heating sources: CHP, solar thermal collectors and heat pump. The electricity demand is provided by the CHP, PV plant and the electricity grid. In the energy model is integrated heat storage tank to maximize the solar fraction from the solar thermal collectors, to balance and optimize the operation of the CHP.

The produced heat by the CHP is2364MWh, with a share of 31.6%. Fig. 6 shows the heating power from CHP in an hourly resolution. Fuel demand for this power plant is 4728MWh, for total load hours of 2292h/year. In summer, no heat is produced by the CHP due to the solar thermal plant and the heat storage that provide the low heat that is needed during the summer. Compared to the study [13], this system will be much greener and will have a positive impact on the environment, as a result of reduced electricity production from combined heat and power plant that uses natural gas as a fuel and increased production of heat by the solar thermal plant. The solar thermal plant generates 1854MWh over the year. This is 24.7% of the heat demand. As presented in Fig. 7, the solar thermal plant provides heat during the whole year. The high-temperature heat storage has a volume of 1740m^3, with a capacity of 40.41MWh and according to the simulation, there are 36 full charging cycles. While working almost during the whole year, with a pause in July and August (Fig. 8), the heat pump generates 3274 MWh with the highest share of 43.7%. The electric demand of the heat pump is 818MWh, assuming that the COP is 4.

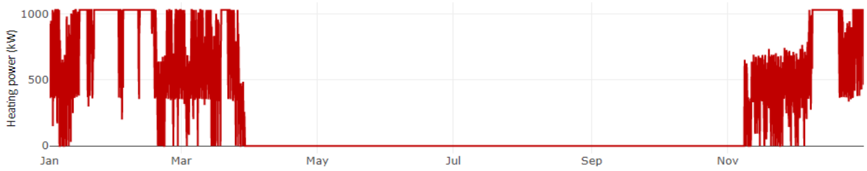

Fig. 6 Combined Heat and Power plant - Produced heating energy annually in hourly resolution

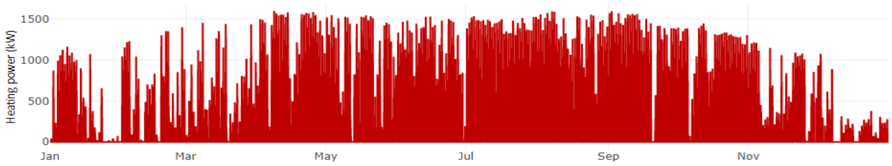

Fig. 7 Solar thermal plant- Produced heating energy annually in hourly resolution

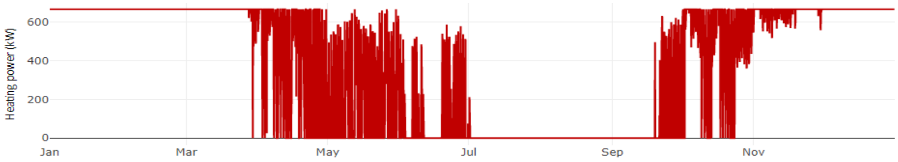

Fig. 8 Heat pump - Produced heating energy annually in hourly resolution

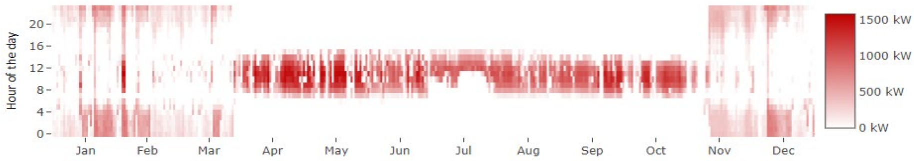

Fig. 9 Heat map – Heat Storage, accumulated thermal power distribution

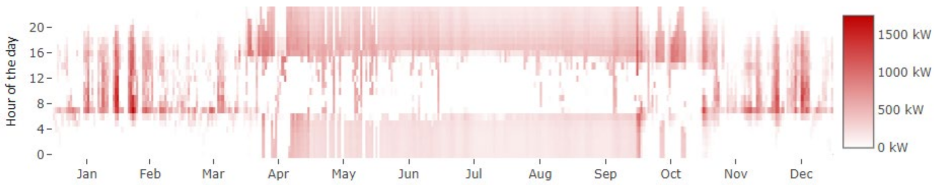

Fig. 10 Heat map –Heat Storage, discharging power

The operation of the thermal storage (Figs. 9 and 10) shows that the storage is charged in the afternoon hours in summer and discharged in the evening/night hours. In the winter the situation is opposite, the storage is mostly charged during the night – when lower quantity of heat is needed and is discharged during the day.

The CHP generate 1655MWh of electricity, with a share of 46%. Fig. 11 shows the electricity generated by the CHP over the year. In summer, no electricity is produced by the CHP due to the electricity generated by the PV plant. This leads to lowered greenhouse gasses emitted by conventional plants. The PV modules generate 1325MWh of electricity over the year (Fig. 12), with 1262 full load hours over the year. The specific electricity production by the PV is 1262MWh/MWp, which is expected for the analyzed location. The annual sum of electricity feed-in is 1066MWh. This is 36.9% of the electricity demand. The rest 17.1% (614MWh) are imported from the grid.

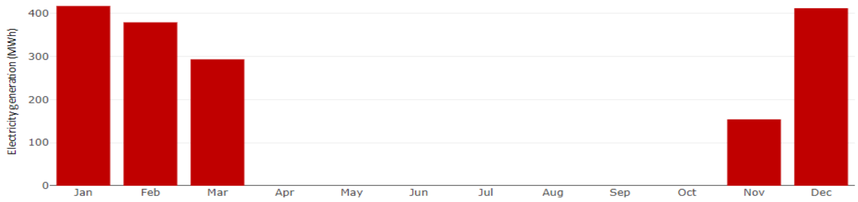

Fig. 11 Combined Heat and Power plant – Produced electricity annually in monthly resolution

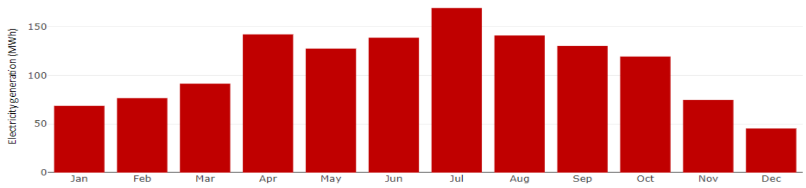

Fig. 12 PV Plant –Produced electricity annually in monthly resolution

The software provides an economic analysis of the energy hub. Fig. 13 demonstrates the cash flow over the year, as well as the net present value (NPV), from which it could be concluded that the ROI period will be about 7 years. A positive NPV at the end of the project life implies that the investment pays off.

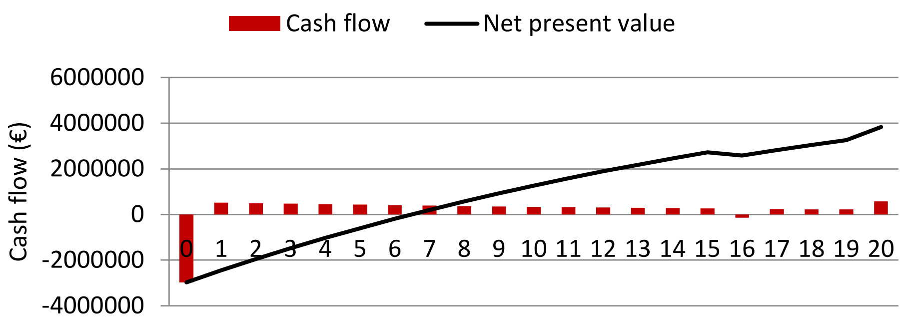

Fig. 13 Economic indicators – cash flow and NPV of the Energy hub for 20 years

The CO_2 emissions are mostly caused by the natural gas fueled CHP, with a value of 1182t, and by the electricity import 368t. There is 53t of CO_2 emissions savings as a result of the feed-in electricity, produced from the PV plant.

6. Conclusions

This paper describes the flexibility that the optimization tool nPro Energy has in order to handle the multiple heat and electricity sources used in energy hubs. In the analyzed model a district heating system with a 7490MWh heat demand and a peak of 3470kW. The heat sources are solar thermal collectors with an area of 2125m^2, CHP plant of 1MWth and a heat pump with capacity of 500kWth. The electricity demand of 1710MWh per year, with an annual peak of 453kW, is provided by a 720 kWel CHP plant and a 1MWp PV plant. The economic analysis indicates positive NPV value and relatively acceptable period of ROI of 7 years. The energy modeling and simulations are carried out in the nPro Energy tool for the heat and electricity demands and design of the components in the energy hub. This energy supply mixes defined to provide a flexible production based on different production units. Optimization results indicates that the symbiosis between district heating systems with integrated renewable energy sources and energy efficient buildings can significantly reduce fossil fuels dependence, resulting in low heating and electricity prices. In order to provide a flexible, stable and cost-effective heating, district heating system is optimal solution mainly because of the possibility for diversification and thus optimization of energy sources in the heat supply.

REFERENCES

1. IEA, 2022, District Heating, IEA, Paris,https://www.iea.org/reports/district-heating, License: CC BY 4.0
2. European commission, 2050 Long Term Strategy, https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en
3. Energy Saving Trust (2020), On the Path to Net Zero: low carbon heating, https://energysavingtrust.org.uk/path-net-zero-low-carbon-heating/
4. European Council meeting (12 December 2019) – Conclusions, EUCO 29/19, Brussels, 12 December 2019
5. IEA, 2022, Global Energy Review: CO2 Emissions in 2021, IEA, Paris https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2, License: CC BY 4.0
6. Cox, Jordan Tracy; Campos, Gustavo; Armatis, Paul; Belding, Scott; Lowder, Travis; Kristensen, Lasse; Zourellis, Andreas; Bless, Frederic; Arpagaus, Cordin; and Baldwin, Samuel F., 2022, Low-Carbon District Heating: Performance Modeling of Hybrid Solar, Heat Pump and Thermal Storage Systems for District Thermal Energy in the United States, International Refrigeration and Air Conditioning Conference. Paper 2380. https://docs.lib.purdue.edu/iracc/2380
7. Ancona, M.A.; Baldi, F.; Branchini, L.; De Pascale, A.; Gianaroli, F.; Melino, F.; Ricci, M., 2022, Comparative Analysis of Renewable Energy Community Designs for District Heating Networks: Case Study of Corticella, Italy. Energies, 15, 5248.
8. Talebi, Behrang & Mirzaei, Parham & Bastani, Arash & Haghighat, Fariborz, 2016, A Review of District Heating Systems: Modeling and Optimization. Frontiers in Built Environment.
9. Solar Heat Worldwide, 2022, Global Market Development and Trends in 2021 / Detailed Market Figures 2020, https://www.iea-shc.org/Data/Sites/1/publications/Solar-Heat-Worldwide-2022.pdf
10. Danish District Heating Association, PlanEnergi, 2018, Solar District Heating, Inspiration and Experiences from Denmark
11. Dario Čulig-Tokić, Goran Krajačić, Borna Doračić, Brian Vad Mathiesen, Robert Krklec, Jesper Møller Larsen, 2015, Comparative analysis of the district heating systems of two towns in Croatia and Denmark, Energy, Vol. 92, Part 3
12. Lipeng Zhang, Oddgeir Gudmundsson, Hongwei Li, Svend Svendsen. Comparison of District Heating Systems Used in China and Denmark. Int. Journal of Sustainable and Green Energy. Vol. 4, No. 3, 2015, pp. 102-116.
13. Element Energy and Carbon Alternatives, 2016, Heat Pumps in District Heating
14. Marco Wirtz, 2023, nPro: A web-based planning tool for designing district energy systems and thermal networks, Energy, Volume 268, 2023, 126575, ISSN 0360-5442
15. https://www.npro.energy/main/en/help/all-tool-features (last access 13.03.2023)
16. State Statistical Office, Prepared by: Stojna Maneva, Gjurgjica Miloshevska, 2023, Electricity and natural gas prices, second semester of 2022, No: 4.1.23.29, https://www.stat.gov.mk/pdf/2023/4.1.23.29_mk.pdf, https://www.stat.gov.mk/PrikaziSoopstenie_en.aspx?rbrtxt=120
17. Ministry of Environment and Physical Planning, 2023, Electricity feed-in tariffs, https://shpp.moepp.gov.mk/373/electricity-tariffs-and-fees