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Field Mechanical Engineering

PhD THESIS
– ABSTRACT –

Energy efficiency of seasonal heat storage systems

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1. Introduction

1.1. General considerations

In the global context of increasing energy demand and climate change concerns, it is necessary to phase out fossil fuels and switch to renewable energy sources (Hussain et al., 2023).

In the European Union (EU), buildings consume 40% of total energy, and the development of buildings will lead to an increase in energy consumption. The primary goals of the EU are related to the reduction of energy consumption and the use of renewable energy sources in buildings, with the aim of reducing the EU's energy dependence on and greenhouse gas emissions (Directiva 2010/31/UE).

In 2018, two-thirds of the total heat supplied in district heating systems in the EU were derived from fossil fuels (Bacquet, 2022). Globally, in 2021, almost 90% of the thermal energy produced in district heating systems is produced from fossil fuels (coal – over 45%, natural gas – approximately 40% and oil – 3.5%), while the share of thermal energy obtained from renewable energy sources is below 8% (IEA, 2022).

In the presented context, solar district heating systems with seasonal heat storage represent a viable solution both for reducing greenhouse gas emissions and for increasing the share of energy produced from renewable sources.

1.2. District heating

In the construction and operation of district heating systems, over time, a noticeable trend has been the continuous reduction of the heating agent's temperature. Currently, fourth generation district heating systems (DHG4) are being implemented worldwide, characterized by flow temperatures in the range of (50 ... 60) °C and return temperatures that are approximately 25 °C (Wiltshire, 2016).

In the context of DHG4, solar district heating systems can be used as an alternative to providing heat in the classic district heating system. Due to the seasonal discrepancy between the availability of solar radiation and the heat demand for heating buildings, it is necessary to implement seasonal storage systems to increase the share of solar energy in district heating systems. Long-term thermal energy storage can also prove beneficial for integrating other heat sources into the system. (H. Lund et al., 2014, 2018).

Currently, fifth generation district heating systems (DHG5) are being studied worldwide and are in the early stage of implementation. These systems are characterized by thermal agent temperatures close to ambient temperature. (Buffa et al., 2019).

In the current context of the development and implementation of DHG4 and DHG5, the study of heat storage systems that contribute to the integration of as much solar energy as possible in district heating systems is topical.

1.3. The integration of solar energy in district heating through seasonal heat storage

In the Scandinavian countries of Denmark and Sweden, as well as in Austria, Germany, Spain and Greece, large-scale solar thermal systems have been in use since the early 1980s. Implementation of such systems was largely achieved in Europe by 2016. In recent years, new large-scale solar thermal systems have also been developed outside Europe, especially in China. By the end of 2021, 530 large solar thermal systems have been commissioned (thermal power greater than 350 kW and minimum area of 500 m^2) (Weiss & Spörk-Dür, 2022).

The evolution of the number of these systems is presented in Fig. 1, and Fig. 2 shows the evolution of the installed solar collector surfaces.

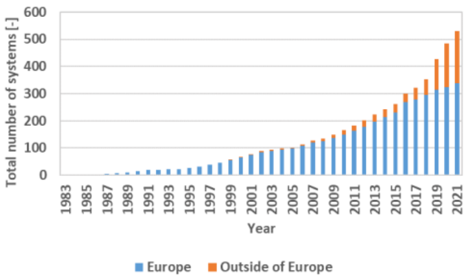

Fig. 1 The evolution of the number of large solar thermal systems (according to Weiss & Spörk-Dür, 2022)

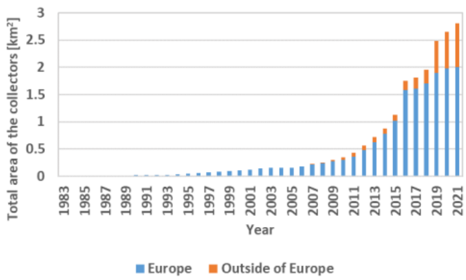

Fig. 2 The evolution of the surfaces of large solar thermal systems (according to Weiss & Spörk-Dür, 2022)

At the end of 2021, there were 299 solar heating systems in the world, with a total solar collector surface of approximately 2.35 km^2 and a total installed thermal power of 1645 MW (Weiss & Spörk-Dür, 2022). The implementation of solar district heating systems in recent years demonstrates the importance of studying seasonal heat storage systems.

1.4. The motivation for choosing the theme

Reducing greenhouse gas emissions, increasing the share of renewable energy sources, and the development of DHG4 and DHG5 are currently of interest, with prospects for the coming years. The global and European context determines the development of solar district heating systems with seasonal heat storage.

The aim of the study is to analyze the energy efficiency of seasonal heat storage systems. The doctoral thesis addresses concerns at the international level in the field of energy.

1.5. The objectives of the doctoral thesis

The objectives of the doctoral research are the following:

- Investigating the state of the art in the field for seasonal heat storage systems, by analyzing the most representative references in the field and by highlighting solutions for seasonal heat storage, along with their characteristic parameters and research methodologies;
- The development of an estimated method for the preliminary sizing of a solar district heating system with seasonal heat storage, considering two scenarios: the first scenario involves available climatic data (annual global solar radiation in the horizontal plane and annual average temperature), while the second scenario deals

with situations where climatic are not known and will be determined using interpolation equations;
- Implementation and validation of a mathematical model for a tank considered to be fully mixed;
- Implementation and validation of a mathematical model based on the finite difference method (FDM) capable of describing the thermal stratification of a seasonal heat storage tank;
- TRNSYS modeling of the behavior of seasonal heat storage stratified tanks;
- Computational Fluid Dynamics (CFD) modeling of the behavior of stratified seasonal heat storage tanks;
- Carrying out a comparison between 3 numerical simulation methods: CFD, FDM and TRNSYS with the aim of cross-validating the results;
- Numerical simulation of a district heating system with seasonal heat storage using TRNSYS and FDM;
- Analysis of the impact of cogeneration systems with heat storage on district heating system by using the stratified tank model developed through analytical method;

2. State of the art

2.1. Seasonal heat storage methods

The period of thermal energy storage varies from a few hours (daily storage) to a few months (seasonal storage). By means of seasonal thermal energy storage systems, it is possible to accumulate the heat available in the summer months to meet the heating load in the winter period (Dincer & Rosen, 2011).

The main methods used for seasonal thermal energy storage are based on forms of sensible heat (Pavlov & Olesen, 2012). Thermal energy storage in the form of sensible heat is achieved by varying the temperature of the storage materials. The amount of heat stored is proportional to the density, specific heat, volume, and temperature variation of the storage materials (G. Li, 2016).

Four main types of seasonal storage are currently in use: tanks, pits, boreholes, and aquifers (Perez-Mora et al., 2018). The most important characteristics of each method are presented below.

Hot water tanks have the following characteristics:
- can be designed regardless of the required geometry;
- structures made of prestressed reinforced concrete or stainless steel;
- the storage medium is water;
- the energy density is 60-80 kWh/m^3;
- frequently insulated with a thick layer of insulation;
- work on the principle of thermal stratification;
- high thermal capacity;
- charge/discharge powers have high values;
- the maintenance and repair of the systems is possible with common technologies.

Pits are defined by the following aspects:
- represents an efficient heat storage solution;
- excavations made in the ground are required;
- the excavations are covered with sheets of polymer materials welded on the sides and bottom of the pit;
- a load-bearing frame is not required for the construction;
- the storage medium is water or a mixture of gravel and water;
- thermally insulate the sides, the bottom of the pit as well as its upper part;
- the energy density is 30-50 kWh/m^3;
- till now, the pits build have volumes up to 200000 m^3;
- disadvantages in maintenance and repair activities;
- disadvantages due to the additional costs generated by covering the pit.

The boreholes have the following characteristics:
- assembly of deep vertical drillings, U-type, which is carried out in the ground or rocks;
- drilling is carried out at depths of 30 – 200 m;
- in the upper part of the borehole, an insulation and a waterproof film are required;;
- thermal losses are relatively high;
- the energy density is 15-30 kWh/m^3;
- limiting the possibility of choosing locations;
- low charge/discharge thermal power.

Aquifers are characterized by the following aspects:
- geological structures that contain groundwater;
- used as a storage medium;
- the groundwater acts as a heating agent;
- permission from the authorities responsible for groundwater is required;
- the energy density is 30-40 kWh/m^3;
- limiting the possibility of choosing locations;
- low charge/discharge thermal power;
- thermal losses are relatively high;
- the impossibility of complete thermal insulation.

In the following, the analysis of seasonal storage systems with hot water tanks is addressed because it represents the most viable solution for implementation in any location.

2.2. The characteristic parameters of seasonal storage in hot water tanks

The constructive characteristics of the hot water tanks are as follows:
- volume (V);
- area/volume ratio (A/V);
- geometric shape;
- height/diameter ratio (h/d) – for cylinders;
- type of location;
- structure;
- insulation;

The analysis of the efficiency of seasonal storage systems is carried out by means of the following parameters:

- overall energy efficiency of the storage process η_{sto} [-];
- energy efficiency of the storage in discharging stage η_{des} [-];
- energy efficiency of the storage in charging stage $\eta_{înc}$ [-];
- exergy efficiency ψ_{sto} [-];
- "Stratification" number Str [-];
- MIX number [-];

2.3. Research methodologies used

Modeling the transient behavior of heat storage tanks is of particular concern in the field of thermal engineering and energy efficiency. Since these tanks are exposed to constant changes in environmental conditions and thermal stresses, understanding and predicting their behavior becomes vital for the design and optimization of heating, air conditioning or hot water production systems.

There are several methods used to model the transient behavior of heat storage tanks, each with its own advantages and limitations. In this context, three of the most frequently used methods will be approached:

- Finite difference method (FDM),
- Numerical simulation with TRNSYS (TRN),
- Finite element simulation of phenomena involving flow (CFD).

3. Preliminary sizing of solar district heating systems with seasonal water thermal storage

3.1 Material and method

The goal of this study is to present a preliminary sizing method dedicated to the solar district heating with seasonal heat storage, based on very few and accessible input data. To the best of our knowledge, such a method is missing from the literature. The main computed values are the aperture area of the solar system and the volume of the seasonal heat storage. Estimations of investments in the solar system and seasonal heat storage are also provided. After this initial step, the final sizing procedure is required. This involves a detailed investigation of the dynamic behavior of the system under the most realistic conditions possible in order to determine the design values of the two key parameters mentioned.

The usefulness and the uniqueness of the proposed preliminary sizing method reside in:

- The simplest available set of input data, in comparison to other available methods
- The capability to provide first guesses for the solar field surface area and the STS volume.

The required input data of the proposed algorithm are:

- The annual heating demand of the consumers - Q_d [MWh/an] ;
- The solar fraction – SF [%];
- The global annual solar radiation on horizontal plane for the location of the system – I_{gh} [kWh/m^2/an];
- The annual average temperature for the location of the system – t_a [°C].

For the regions without available annual global solar radiation and annual average temperature, the latitude of the location is required, and the missing data are calculated as a function of the latitude. For this purpose, interpolation functions were developed based on the available data from 144 randomly chosen locations, distributed worldwide.

Based on the presented equations, Fig.3 shows the flow chart of the preliminary sizing algorithm.

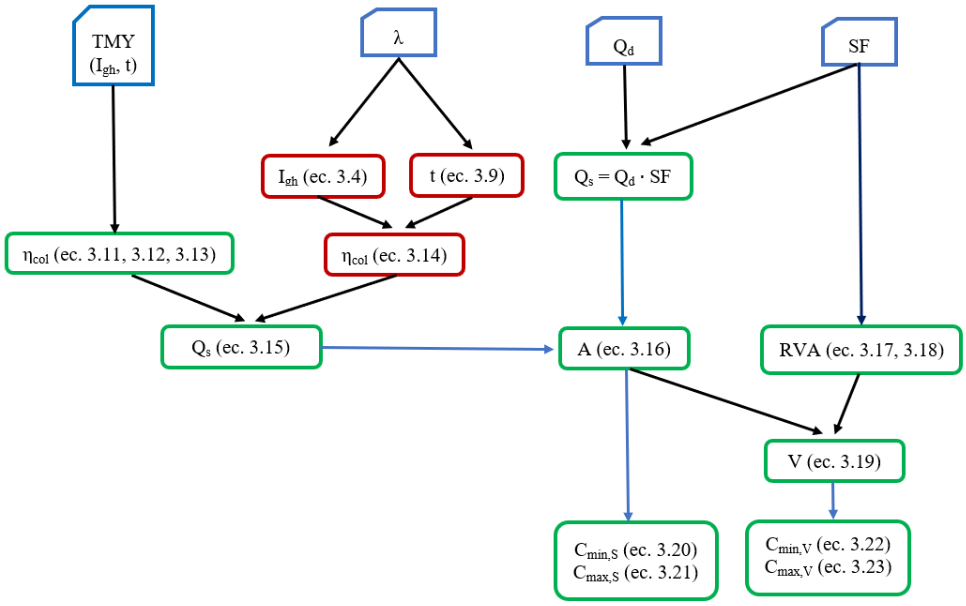

Fig. 3 Flow chart of the preliminary sizing algorithm

The parts of the calculation algorithm that specifically depend on the method used are highlighted with red lines. If climate data from TMY is available, it should be used as input to the application. The preliminary sizing application for solar district heating systems with seasonal heat storage, when using the equations obtained through interpolation, was developed in the Python programming language.

The errors of the interpolation equations were determined as follows:

- For the global solar radiation on horizontal plane in the range of (-15.6 … +25.8) %.
- For the annual average temperatures in the range of (-4.23 ... +5.37) °C.
- For the annual global efficiency of the solar thermal collectors in the range of (-10.8 … 19.1) %.

Due to the limited accuracy, the interpolation functions are valid for calculating the annual global solar radiation in the horizontal plane in the range of (704 … 2337) kWh/m^2/year and the average annual temperature in the range of (2 … 30) °C. As a result, it is possible to calculate the annual global efficiency of solar thermal collectors, the aperture area of solar thermal collectors, and the volume of seasonal heat storage within the same valid range.

To estimate the costs of both solar thermal collectors and seasonal heat storage tanks, interpolation functions based on references from 2012 were used. However, it has been demonstrated that these functions remain valid for systems built or simulated in recent years.

3.2 Results

The proposed method for the preliminary sizing of solar district heating systems with seasonal heat storage was tested for 14 existing systems in Europe, Canada, and China.

By comparing the calculated and the existing characteristic parameters of the solar district heating with seasonal heat storage, the number of cases in which the values were reasonably determined, based on the available TMY, are as follows:

- The efficiency of the systems in over 60 % of cases;
- The aperture area in over 33 % of cases;
- The storage volume in 75 % of cases.

The interpolations yielded accurate values for:

- The efficiency of the systems in over 40 % of cases;
- The aperture area in almost 70 % of cases;
- The storage volume in over 70 % of cases.

4. Modeling of district heating systems with seasonal heat storage

4.1. Configuration of district heating systems with seasonal heat storage

Fig. 4 presents scheme of the solar district heating system with seasonal storage.

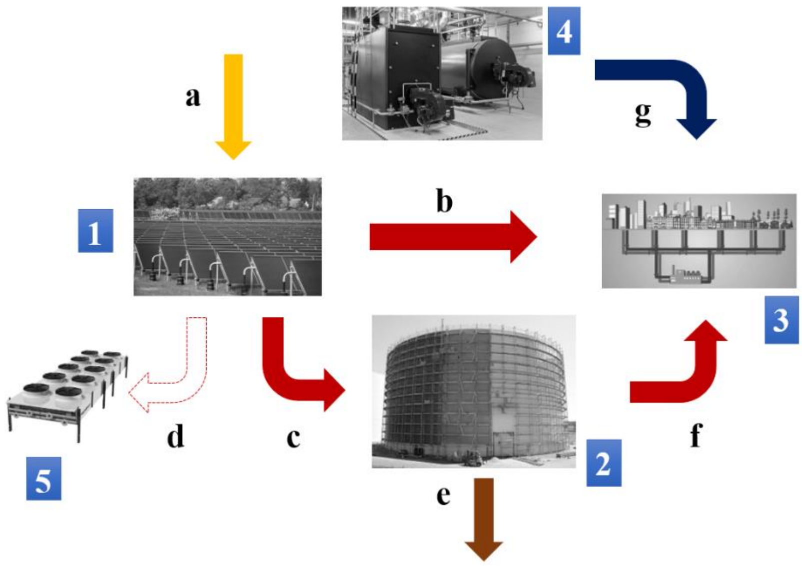

Fig. 4 Scheme of the solar district heating system with seasonal storage
1 – Solar collectors; 2 – Seasonal storage hot water tank; 3 – Residential heat consumer; 4 – Auxiliary heating source; 5 – Dry cooler;
a – Solar radiation received (Q_r); b – Solar energy for heating (Q_{sh}); c – Solar storage heat (Q_{st}); d – Excess solar heat (Q_{sx}); e – Heat losses (Q_l); f – Solar storage heat (Q_{ss}); g – Auxiliary heat from gas boiler (Q_g)

The solar radiation (Q_r) is the global solar radiation on the horizontal plane, available in the considered location, representing the local potential of the solar harvesting. The solar field (1) provides the solar heat (Q_s) that is either distributed directly to the heat consumers (Q_{sh}) or to the storage tank (2). The heat accumulated in the tank (Q_{st}) can be used in the district heating system (3) when the heating load can't be provided completely by the solar field. The heat losses (Q_l) are determined by the temperature difference between the water inside the storage tank and the exterior. When there is no or very low heat demand and the storage tank is already heated at the upper temperature limit, the possible excess solar heat (Q_{sx}) must be evacuated.

The district heating load (Q_d) can be provided either by the solar field (Q_{sh}), by the seasonal storage tank (Q_{ss}), by the backup gas boiler (Q_g) or by any combination of the three heat components.

4.2. Calculation elements. Mathematical models

The chapter contains a synthesis of the calculation elements of the system, in which the parameters are defined and explained. In the case of the analytical method, the calculation relations used are presented, and in the case of TRNSYS, the modules used in the modeling of district heating systems are described.

The thermal behavior of seasonal heat storage tanks is evaluated by means of 3 mathematical models:

- Fully mixed tank, developed by the analytical method;
- Stratified tank, developed by the analytical method;
- Model implemented in TRNSYS (can be of fully mixed or stratified tank).

The differences obtained when using different analysis methods are specified by calculation deviations:

- Mean Deviation (MD);
- Mean Bias Error (MBE);
- Root Mean Square Error (RMSE);
- Relative deviation (ε).

4.2.1 The fully mixed tank model

The fully mixed storage tank model is usually used for quick and indicative calculations because real tanks are neither fully mixed nor fully stratified (Duffie & Beckman, 1980). Fig. 5 presents the energetic scheme of the fully mixed seasonal storage tank.

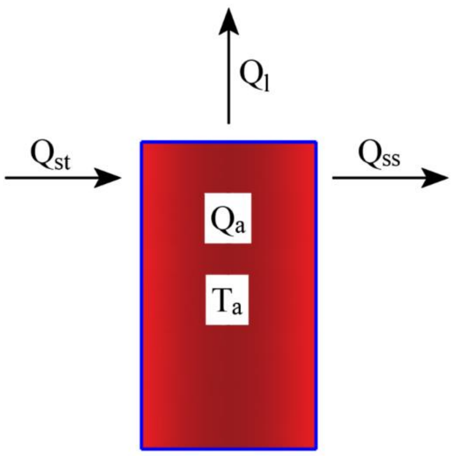

Fig. 5 Energetic scheme of fully mixed seasonal storage tank

Q_{st} – the share of the heat provided by the solar field that is stored into the tank seasonal storage; Q_l – heat losses; Q_{ss} – heat discharged from the tank seasonal storage into the district heating system; Q_a – heat accumulated in tank seasonal storage; T_a – water temperature inside tank seasonal storage.

4.2.2 The stratified tank model

The simulation of the thermal behavior of the storage tank is achieved using a 1D analytical model based on the finite difference method. The transition from the real storage tank model to the discretized tank is illustrated in Fig. 6. The real tank (Fig. 6.a) is divided into n layers or control volumes, resulting in the discretization scheme (Fig. 6.b). Each control volume is considered to be fully mixed, with a constant water temperature. The resulting mathematical model (Fig. 6.c) enables the modeling of the thermal behavior of the storage tank.

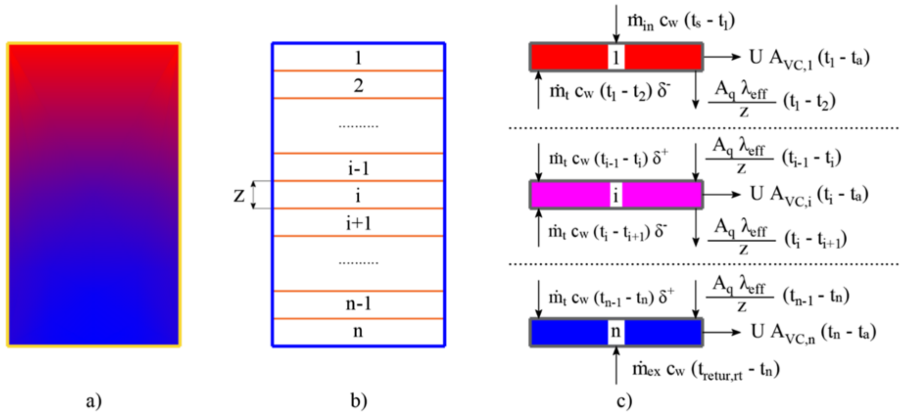

Fig. 6 The discretization scheme and the basics of the mathematical model
a) The real tank; b) The discretized tank; c) The mathematical model.

The principles of the analytical model of the heat storage tank are presented in (Eicker, 2005; Hiris et al., 2022a; Hiris et al., 2020; Sinha et al., 2019). The control volumes (1…n), counted from top to bottom, are considered fully mixed, and the heat transfer between the control volumes is considered unidirectional.

4.2.3 The tank model implemented in TRNSYS

The modeling of a stratified storage tank in TRNSYS is implemented in the 4d module called *Stratified Fluid Storage Tank*, with the mathematical description presented in (Klein et al., 2007, 1976). Model 4D assumes that heat losses are non-uniform, and the fluid inlet connections in the tank have variable positions, depending on the temperature distribution. The storage tank can be discretized into n nodes (control volumes), with each control volume considered completely mixed (uniform temperature distribution within the control volume). The maximum number of nodes used in discretization is 100. If n = 1, the tank is fully mixed. Fig. 7 presents the scheme for the discretization of the stratified storage tank used in TRNSYS.

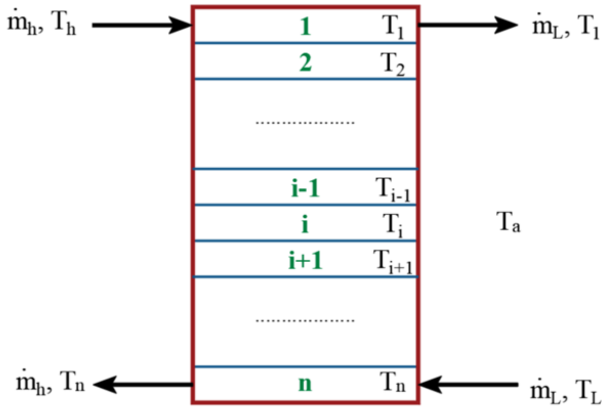

Fig. 7 Discretization of the stratified storage tank used in TRNSYS

5. Validation of storage tank models

5.1. Validation of the fully mixed tank model

The model was validated using data from the literature (Guadalfajara et al., 2014b) based on previously developed calculation methods (Braun et al., 1981; Lunde, 1979). The solar district heating system is located in Zaragoza (Spain).

The variation of water temperature in the storage tank is shown in Fig. 8.

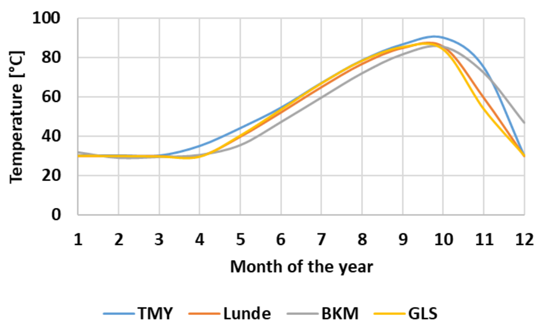

Fig. 8 Variation of water temperature in the storage tank

The comparative analysis carried out for the values of the main parameters of solar district heating systems with seasonal heat storage, obtained by the model developed in this work based on TMY climate data and the Lunde, BKM, GLS models used for calculation in

(Guadalfajara et al., 2014b), leads to the conclusion that the TMY model is validated. The differences in the annual results are as follows:

- A higher range of (1.1% to 3.7%) for incident energy values on the inclined plane;
- A 1.2% lower range for heat load values;
- A range of (11% to 16%) for heat losses;
- A higher range of (7.9% to 12.7%) compared to Lunde and BKM, and a 0.4% lower range compared to GLS for heat produced by the natural gas boiler;

5.2. Validation of the stratified tank model through FDM and TRNSYS

The models describing the thermal behavior of the stratified tank, one developed by the analytical method and another implemented in TRNSYS, underwent validation by comparing their results with those of five numerical simulations from the literature. The results demonstrate the following:

- When comparing with the results from (Eicker, 2005), the maximum temperature difference between the calculated temperature and the reference work's temperature is consistently below 1.3°C in all layers. MD remains below 0.25°C, while MBE and RMSE show differences of less than 1.6%.
- In the case of results obtained in (Sinha et al., 2019), the maximum temperature difference is below 1.6°C in all control volumes, with MD values below 0.2°C, MBE below 0.4%, and RMSE below 0.65%.
- In comparison with the results from (Scolan et al., 2020), the maximum temperature difference is below 2.11°C in all layers, with MD below 0.27°C, MBE below 0.7%, and RMSE values lower than 0.9%.
- When compared to the results from (Bastida et al., 2019), the maximum temperature difference is below 2.35°C, MD is below 0.55°C, MBE below 1.1%, and RMSE is below 1.4%.
- In the case of comparison with the results from (Morales Sandoval et al., 2021), the maximum temperature difference is below 1°C in all layers, MD values are below 0.16°C, MBE is below 0.4%, and RMSE shows differences below 0.45%.

5.3. Cross-validation of methods for investigating the behavior of storage tanks

In the following section, we investigate the heating process of a heat storage tank using various simulation methods. The tank is described in detail in (Dzierwa et al., 2022). This study was selected because it involves a comparison between an experimental study and a numerical simulation conducted using the CFD method. The results obtained in this study serve as references for further research. The three simulation methods employed in this study are: FDM, TRNSYS, and CFD.

The storage tank has a cylindrical shape and is connected to a cogeneration system. A circular inlet connection is located at the upper part of the tank for admitting hot water, while an identical circular outlet connection is situated at the lower part of the tank for discharging hot water.

Fig. 9 illustrates the geometric characteristics of the storage tank.

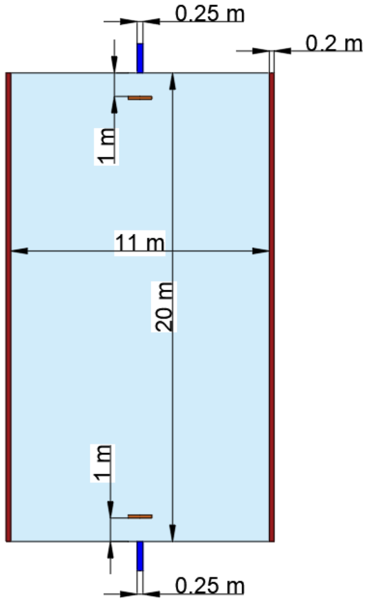

Fig. 9 The geometric characteristics of the storage tank.

CFD simulation is conducted in ANSYS Fluent R22 R2. The chosen model is 2D axisymmetric.

Fig. 10 displays the geometric model of the storage tank and the established boundary conditions for this study.

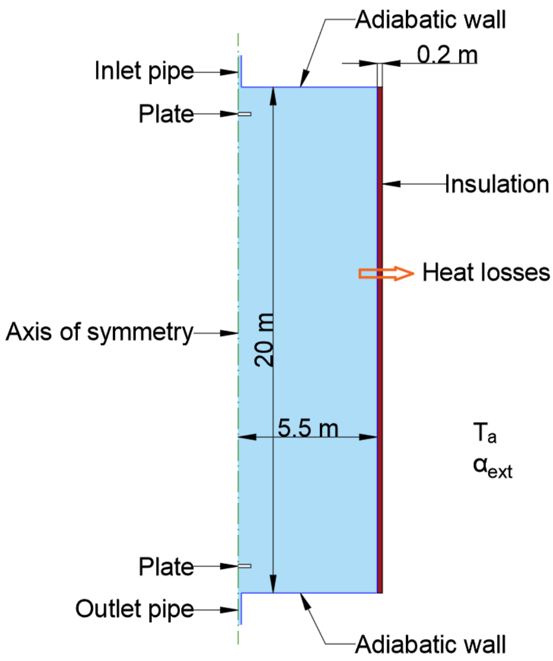

Fig. 10 The geometric model of the storage tank and the boundary conditions

Initially, the accuracy of the CFD model implementation was verified. The comparison between CFD-I and CFD-R revealed insignificant differences in the results: MD was below 0.36°C, MBE was below 0.6%, and RMSE was below 1.26%. The determined heat losses were also very close and fall within the range of (12.97 ... 16.39) W/m^2 for CFD-I and (12.87 ... 16.51) W/m^2 for CFD-R.

Next, the influence of heat losses on the temperature distribution along the tank's height was analyzed using two calculation hypotheses: the isolated tank and the adiabatic tank. The differences between the results obtained in these two cases were negligible: MD was below 0.4°C, MBE was below 0.4%, and RMSE was below 1.2%. To simplify the study, only the adiabatic tank hypothesis was used, neglecting heat losses.

Subsequently, the validation of the models developed through FDM and TRNSYS was conducted. A coarse discretization was applied, using 20 and 40 control volumes (the maximum limit that could be implemented in TRNSYS). The results showed that there were insignificant differences between the two calculation methods: MD was below 0.07°C for 20 control volumes and below 0.2°C for 40 control volumes, MBE was below 0.085% for 20 control volumes and below 2% for 40 control volumes, and RMSE was below 0.15% for 20 control volumes and below 2.05% for 40 control volumes. Although the results of the two methods closely resembled each other, they deviated significantly from the experimentally determined values. It was concluded that TRNSYS is not recommended for this type of study, and it was identified that the accuracy of FDM can be improved by increasing the number of control volumes.

In the following section, we explored the impact of discretization quality on the calculation accuracy of the FDM by employing 100, 200, 300, and 500 control volumes. Our findings indicated that as the model's discretization accuracy increased, so did the accuracy of the results, bringing them closer to both experimental data and CFD-R results. It was even demonstrated that in certain aspects, the MDF simulation with 500 control volumes was even closer to the experiment than the results obtained by CFD. For instance, this was observed in the temperature distribution within the transition zone and the position of the transition zone at the end of the heating process.

The impact on simulation accuracy, as determined by altering the water temperature at the inlet of the storage tank from 94°C (Dzierwa et al., 2022) to 96°C, indicates that it is more accurate to consider a value of 96°C for the water temperature entering the tank.

A comparison of simulation durations related to the tank heating process was conducted, highlighting the advantages and limitations of each calculation method used in this study:

- TRNSYS is not recommended for accurately investigating relatively short-duration processes (less than a day) due to limitations in discretization accuracy. However, it can be successfully used to explore the transient behavior of storage tanks over longer time periods (several months, a year, or more),
- CFD allows for the most accurate simulations of short-term processes but, due to the lengthy simulation times, it cannot be employed for investigating long-term processes (the longest simulated period found in the literature being 27 hours),
- FDM is a versatile and flexible method that enables both accurate simulation of relatively short processes (under a day) and long-lasting processes (over a year) with slightly less precision.

The primary findings of the studies conducted in this chapter indicate that simulations performed using the CFD method yield results similar to experimental ones, while those conducted using the FDM method provide the most satisfactory results, with improved precision achieved by increasing the number of control volumes. Furthermore, the importance of considering the water temperature at the tank inlet was emphasized, and the advantages and limitations of each calculation method were highlighted.

6. Numerical simulation of district heating systems with seasonal heat storage

6.1. Description of the investigated system

The investigation was focused on a residential area of Cluj-Napoca, located in the area of Timișului - Blajului streets. The study aims to provide the heat demand for building heating and domestic hot water (DHW) preparation through a solar thermal system with seasonal heat storage and is carried out both by simulation using TRNSYS and analytical modeling. Two climate databases were used as a source for input data: EnergyPlus and Meteonorm.

The calculation conditions for the solar district heating system with seasonal heat storage are summarized in Tab. 1.

Tab. 1 The parameters of solar district heating system with seasonal heat storage

System component	Parameter	Value	U.M.
Heat consumers	Thermal characteristic of the buildings	22.95	kW/K
	Temperature inside the buildings	20	°C
	Ambient temperature under which the heating system is set on	12	°C
	Temperature on the return of the thermal network	50	°C
	Number of persons	945	-
	Quantity of DHW consumed daily by each person	30	l/person/day
	Temperature of the prepared DHW	60	°C
Solar system	Aperture of solar thermal collector	12.56	m^2
	Optical efficiency	0.838	-
	Thermal losses coefficient 1	2.46	W/m^2K
	Thermal losses coefficient 2	0.0197	W/m^2K^2
	Number of solar thermal collectors	140	buc
	Total aperture of solar thermal system	1758	m^2
	The flow temperature of the solar field	95	°C
Tank heat storage	Maximum temperature	95	°C
	Minimum temperature	50	°C
	Volume	8500	m^3
	Report between height and diameter	0.6	-
	Diameter	26.23	m
	Height	15.74	m
	Thermal insulation conductivity	0.035	W/mK
	Thermal insulation width	0.4	m

Fig. 11 presents the 3D model of the residential area, with the solar thermal collectors mounted on the roofs.

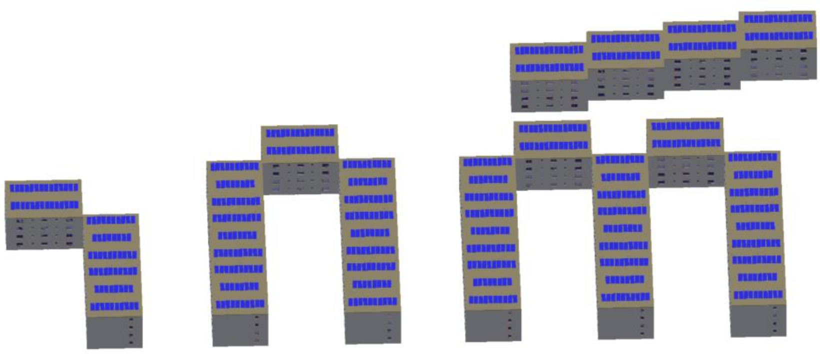

Fig. 11 The 3D model of the residential area, with the solar thermal collectors on the roofs.

Fig. 12 presents the scheme of the solar district heating modeled both by analytical method and in TRNSYS, using the TRNSYS symbols.

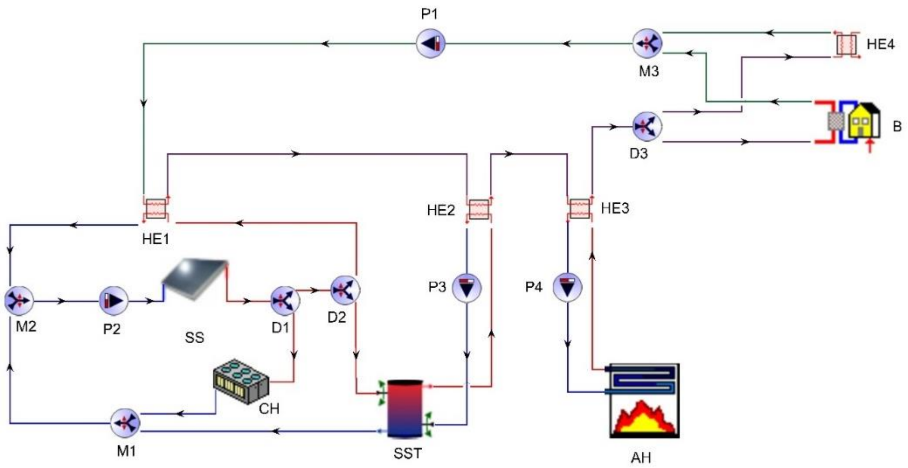

Fig. 12 The scheme of the solar district heating with seasonal heat storage
B – Heat consumers (*Buildings*); SS – Solar thermal system; SST – Seasonal storage tank; AH – Auxiliary heating source; HE1, HE2, HE3, HE4 – Heat exchangers; P1, P2, P3, P4 – Circulation pumps; M1, M2, M3 – Mixers; D1, D2, D3 – Diverters; CH – Air cooled chiller.

The heat consumers (B) are supplied with energy from the three heat exchangers (HE1, HE2, HE3). The circulation of the heat agent on the circuit of the heat exchangers, on the side that serves the consumers, is ensured by the pump with variable speed (P1). The heat exchanger (HE1) supplies heat from the solar system (SS). The mixer (M1) unites the thermal agent flows coming from the heat exchanger (HE1), the air-cooled chiller (CH) and the storage tank (SST), the resulting flow being transported through circuit using the pump (P2). The diverter (D1) divides the fluid flow leaving the solar system (SS) into two parts: one part goes to the air-cooled chiller (CH) and another part goes to the diverter (D2). From the diverter (D2) the flow is divided into two parts: one part reaches the storage tank (SST) and another fraction of the flow reaches the heat exchanger (HE1). The flow to the storage tank (SST) is determined according to the ratio between the thermal energy production of the solar system and the heat demand. The seasonal storage tank (SST) supplies heat to the heat exchanger (HE2) when the heat demand cannot be fully provided by the heat exchanger (HE1), the circulation of the thermal agent on this circuit being ensured by the circulation pump with variable speed (P3). The auxiliary heat source (AH) represented by a natural gas boiler comes into operation when the heat requirement is not fully provided by the heat exchangers (HE1) and (HE2). Heat provided by the auxiliary source is transferred to the heat exchanger (HE3), the circulation of the thermal agent in this circuit being ensured by the pump with variable speed (P4). The heat required by the consumers is divided by the diverter (D3) into two parts: one part provides the heat requirement of the buildings, and the other part provides the heat requirement for the preparation of DHW. DHW is prepared by the heat exchanger (HE4). The mixer (M3) brings together the flows from buildings (B) and from (HE4). The air-cooled chiller (CH) takes over the excess heat produced by the solar collectors, only coming into operation in emergency situations.

6.2. Comparative results

Fig. 13 and 14 presents the hourly variation of the total heat load, for heating and DHW, with the climatic data from EnergyPlus and Meteonorm respectively.

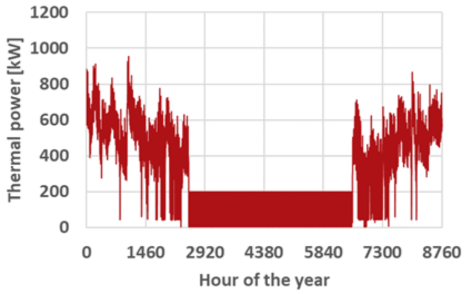

Fig. 13 The hourly variation of the total heat load for EnergyPlus

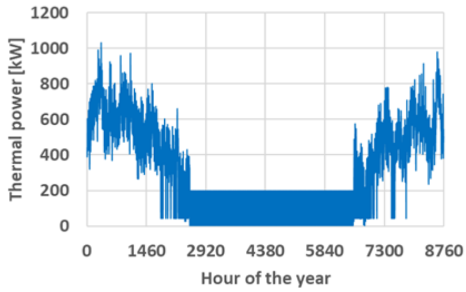

Fig. 14 The hourly variation of the total heat load for Meteonorm

The hourly temperature variation in the upper layer (layer 1) of the SST computed with EnergyPlus is presented in Fig. 15 and the same variation computed with Meteonorm is presented in Fig. 16.

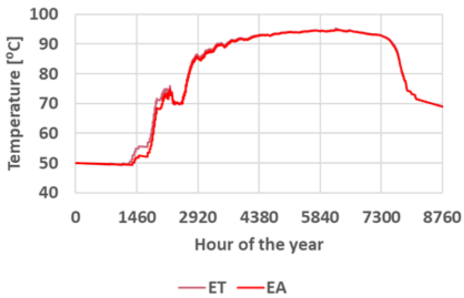

Fig. 15 The hourly temperature variation in the layer 1 of the seasonal storage water tank with EnergyPlus

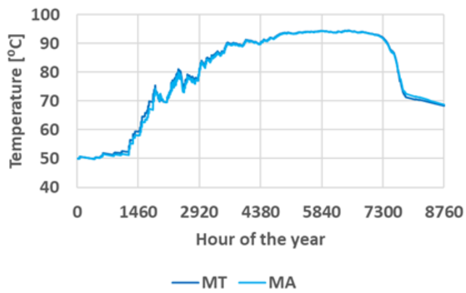

Fig. 16 The hourly temperature variation in the layer 1 of the seasonal storage water tank with Meteonorm

The hourly temperature variation in the lower layer (layer 10) of the SST computed with EnergyPlus is presented in Fig. 17 and the same variation computed with Meteonorm is presented in Fig. 18.

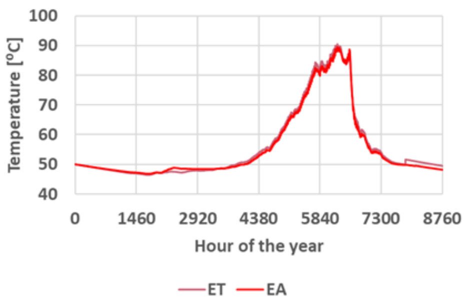

Fig. 17 The hourly temperature variation in the layer 10 of the seasonal storage water tank with EnergyPlus

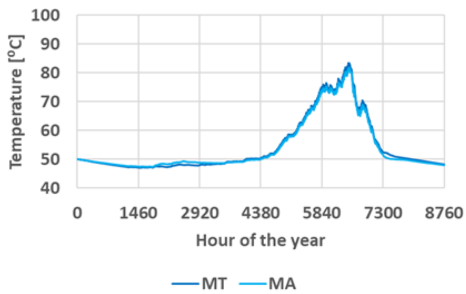

Fig. 18 The hourly temperature variation in the layer 10 of the seasonal storage water tank with Meteonorm

The differences between the temperatures in the different layers of the seasonal storage water tank computed with EnergyPlus and Meteonorm, are presented in Tab. 2.

Tab. 2 Differences between the temperatures in the different layers of the seasonal storage water tank

Strat [-]	EnergyPlus				Meteonorm			
	Δt_{max} [°C]	MD [°C]	MBE [%]	RMSE [%]	Δt_{max} [°C]	MD [°C]	MBE [%]	RMSE [%]
1	4.1646	0.5400	0.6330	1.2704	2.8336	0.3889	0.5827	0.8750
5	5.0077	1.0255	1.6121	2.6269	4.7104	0.9289	1.3935	2.4890
6	6.1071	1.1039	1.8308	3.0856	4.4804	0.8944	1.5266	2.5612
10	2.1297	0.4314	1.3293	1.6015	1.9662	0.3242	1.1314	1.3394

Fig. 19 shows the annual solar fraction values for the solar district heating system with seasonal heat storage presented in this study.

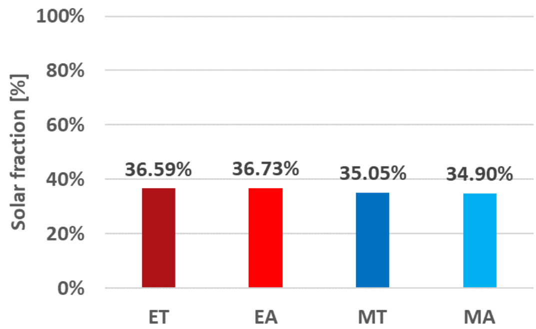

Fig. 19 The annual solar fraction for the analyzed solar district heating system

6.3. Conclusions

The results of the numerical simulation indicate coherence between the analytical method and TRNSYS, demonstrating yearly calculation differences for the main parameters investigated:

- In the case of incident energy on a tilted plane, for EnergyPlus, the results obtained with ET are 0.8% higher than EA, and for Meteonorm, the value obtained with MT is 3.8% higher than MA.
- For solar energy production, in the case of EnergyPlus, ET produces 1.12% more solar energy than EA, and for Meteonorm, MT produces 2.0% more solar energy than MA.
- Regarding heat losses, for EnergyPlus, ET measures heat losses 3.8% higher than EA, while for Meteonorm, the value obtained with MT is 3.6% higher than MA.
- For solar thermal energy delivered directly to consumers, in the case of EnergyPlus, EA delivers 4.2% more solar heat than ET, and for Meteonorm, MT delivers 7.4% more solar heat to consumers than MA.
- For the thermal energy provided to the tank, in the case of EnergyPlus, 5.2% more heat is accumulated in the tank through ET than through EA, and for Meteonorm, 1.6% more heat is accumulated in the tank through MT than through MA.
- In terms of thermal energy provided from the tank, in the case of EnergyPlus, ET delivers 1.7% more heat from the tank than EA, and for Meteonorm, MA delivers 2.8% more heat from the tank than MT.
- For the thermal energy provided by the natural gas boiler, in the case of EnergyPlus, ET delivers 0.08% more heat from the boiler than EA, while for Meteonorm, MA delivers 0.35% more heat from the boiler than MT.

- The energy efficiency of the storage tank is higher for EnergyPlus, with EA being 2.73% more efficient than ET, and for Meteonorm, MA's seasonal storage tank is 3.49% more efficient than MT.

From the results presented in this study, the viability of using TRNSYS and the analytical method in the simulation of district heating systems with seasonal heat storage is demonstrated.

7. The impact of cogeneration plant in a district heating system

7.1. Introduction

The coupling between the combined heat and power (CHP) plant with thermal engines with a large water storage tank (WST) allows to increase the flexibility of the system. The thermal energy storage removes the operation of the engine on partial load with many starts and stops and has a positive effect on the performance and lifetime of the system (Fragaki et al., 2008). If the CHP is coupled with a WST the economic efficiency can be improved allowing to run the engines when the price of the produced electricity is high, even if there is not enough thermal energy consumption in the same period (Streckiene et al., 2009).

7.2. Material and method

The investigated system is located in Vatra Dornei, Romania. The existing heat source consists of two biomass boilers, each with a capacity of 6 MW. It is proposed to add a combined heat and power plant with two natural gas-fired engines, each with an electric power output of 1500 kW and a thermal power output of 1600 kW. Additionally, a water storage tank with a capacity of 300 m^3 is proposed. The size of this tank was determined through several consecutive iterations, considering that the storage volume must be suitable for both heating and cooling modes, particularly during the summer when the heat load is low and only one engine is used. The water storage tank has a diameter of 8.6 m and a height of 5.16 m, divided into 10 control volumes, each with a height of 0.516 m.

The scheme of the system is presented in Fig. 20.

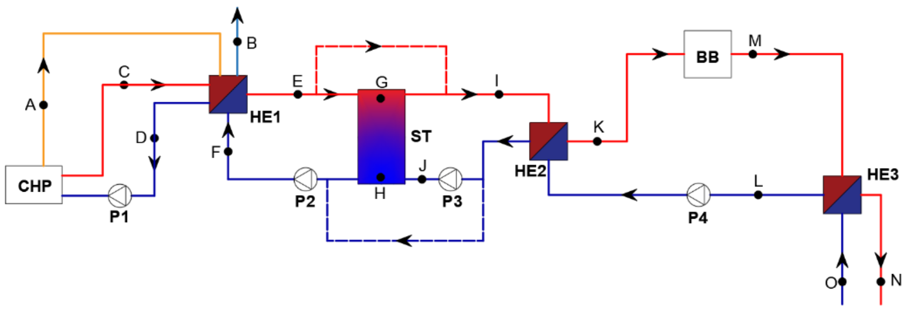

Fig. 20 The scheme of the district heating system placed in Vatra Dornei, Romania
Abbreviations: CHP – Cogeneration system (2 x 1500 kW$_{el}$); ST – WST (300 m^3); BB – Biomass boilers; HE1, HE2, HE3 – Heat exchangers; P1, P2, P3, P4 – Recirculation pumps.

The chosen nominal temperatures in the characteristic states of the system are presented in Tab. 3.

Tab. 3 Nominal temperatures in the characteristic states [°C]

Position	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Winter	374	120	82	70	87	J	min. 75	J	G	L+5	I-5	O+5	N+10	f(t_{ex})	50
Summer	374	120	82	70	87	J	min. 75	J	G	L+5	I-5	45	N+10	f(t_{ex})	10

These nominal temperatures differ between summer and winter. In summer, when only domestic hot water (DHW) is required, the provided temperature of the thermal agent can be lower than in winter when heating is also needed. Consumer heating systems typically require higher temperatures, often utilizing high-temperature radiators.

The flow temperature throughout the year is depicted in Fig. 21, and Fig. 22. illustrates the hourly variation of the heat load for both heating and DHW.

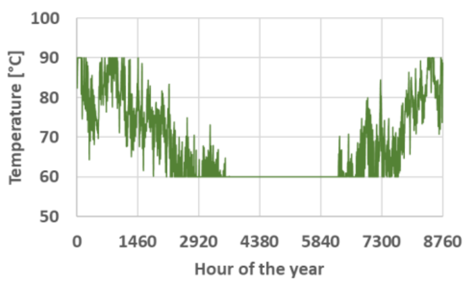

Fig. 21 Flow temperature variation during the year

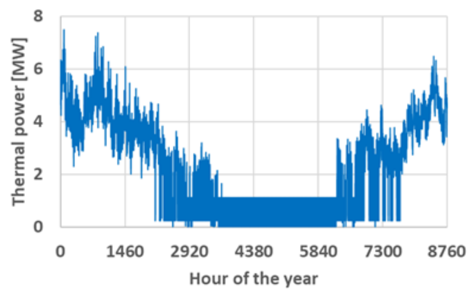

Fig. 22 Hourly heat load

7.3. Results and discussion

The simulation computed the hourly variation of several parameters, including:

- Temperatures and flow rates in all characteristic states of the district heating system,
- Temperatures distribution inside the water storage tank,
- Thermal and electric power generated by the combine heat and power engines,
- Thermal power generated by the biomass boiler,
- Thermal power transferred through the heat exchangers,
- Thermal power introduced into and extracted from the water storage tank.

A typical comparison between the thermal power generated by the combined heat and power engines and the thermal power consumed by the district heating consumers, both in winter and summer conditions, is presented in Fig. 23 and 24 respectively.

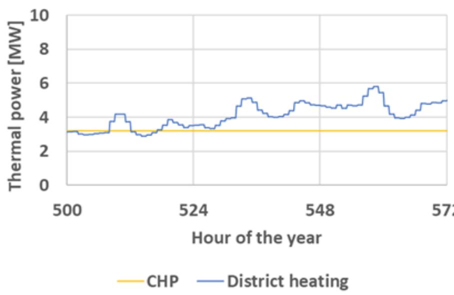

Fig. 23 The thermal power provided by the CHP plant and consumed by the district heating in winter (3 typical days).

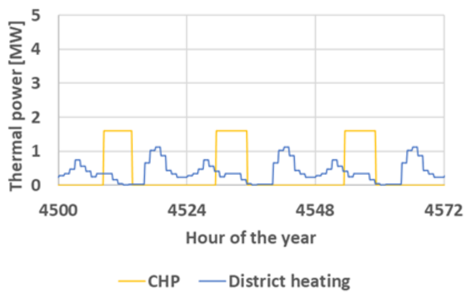

Fig. 24 The thermal power provided by the CHP plant and consumed by the district heating in summer (3 typical days).

In winter, the water storage tank will not be used as it would rapidly lose heat, making it challenging to maintain its temperature. In summer, even a single CHP engine can provide more thermal power than the required DHW heating power. Under these conditions, only one CHP engine will be in operation, and the water storage tank will enhance system flexibility. The key advantage is that the engine can primarily run during periods when electricity prices are high.

A typical temperature variation inside the WST control volumes, in 3 consecutive days of summer, is presented in Fig. 25.

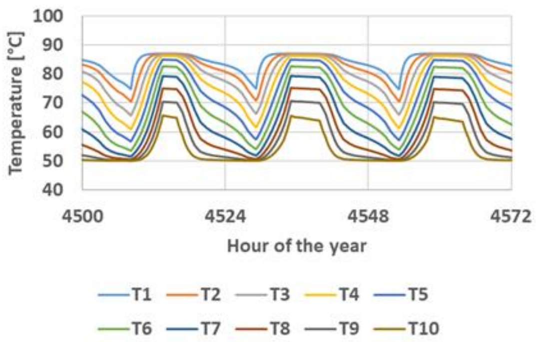

Fig. 25 Typical temperature variation inside the WST control volumes, in 3 consecutive days of summer.
T1...T10 – The temperatures in the control volumes (numbered from top to bottom).

The temperature distribution inside the WST during the charging period is presented in Fig. 26, and during the discharging period is presented in Fig. 27.

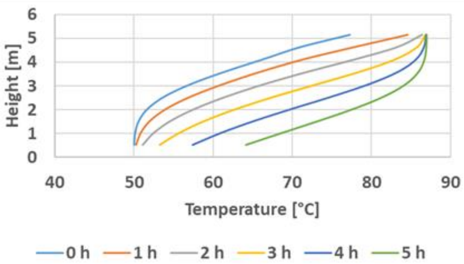

Fig. 26 The temperature distribution inside the WST in the charging period.

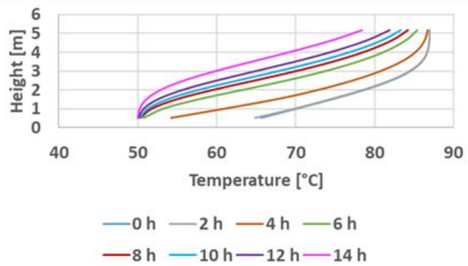

Fig. 27 The temperature distribution inside the WST in the discharging period.

The annual heat flow Sankey diagram of the whole district heating system, in MWh, is presented in Fig. 28.

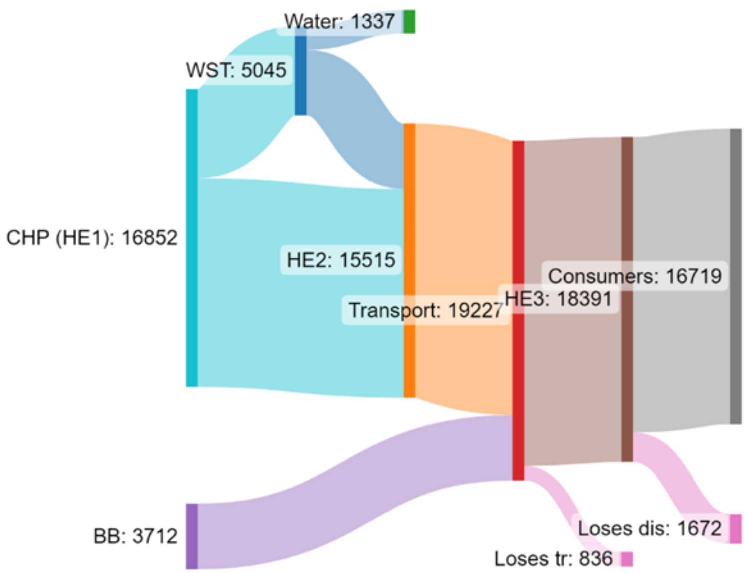

Fig. 28 Sankey diagram of the heat flow in the district heating system (in MWh)

The global yearly heat balance is confirmed:
- Produced heat: 20564 MWh;
- Consumed heat: 20564 MWh.

7.4. Conclusions

The analysis presented for the district heating system, which integrates a natural gas CHP plant and a WST into an existing system based solely on biomass, proves that this cohabitation is possible and offers advantages primarily due to the increased flexibility of the system. Such investigations can be successfully implemented in other district heating systems.

8. Final conclusions

8.1. General conclusions

The research conducted during the doctoral program aims to analyze the energy efficiency of seasonal heat storage systems and is structured as follows:
- Review of the state of the art in the investigated field.
- Preliminary sizing of solar district heating systems with seasonal heat storage;
- Modeling of district heating systems with seasonal heat storage;
- Validation of the mathematical models that describe the thermal behavior of the storage tank;
- Comparative numerical simulation, using both analytical methods and TRNSYS, of district heating systems with seasonal heat storage;
- Study on the impact of cogeneration in district heating system.

8.2. The originality and innovative contributions of the thesis

The doctoral study addressed the topic of energy efficiency in seasonal heat storage systems and included original contributions.

The state of the art in the investigated field revealed significant personal contributions:
- A comparative presentation of seasonal storage methods was conducted, highlighting the advantages and limitations of each method;
- The most representative construction and efficiency parameters of heat storage tanks were presented;
- Research methodologies employed in the field were analyzed, with a focus on their advantages, limitations, and potential for study development.

Following the completion of the study, it was discovered that this field remains largely unexplored in Romania. The doctoral thesis, along with the published articles, represent pioneering contributions to the field, at least at the national level.

The preliminary sizing of solar district heating systems with seasonal heat storage brings the following novelties at the scientific level:
- This approach is conducted for the first time in the specialized literature
- The presented method aims to determine, during the preliminary design phase, the surface area of the solar thermal system and the volume of seasonal heat storage;
- The developed algorithm is based on a limited set of easily accessible input data;

- For regions of the globe where climate data are unavailable, interpolation equations have been proposed based on the location's latitude;
  The algorithm offers the possibility of cost analysis for the primary components of solar district heating systems, including the solar field and the seasonal storage tank.

The modeling of district heating systems with seasonal heat storage yields the following original contributions:

- Proposes a reference configuration for a solar heating system with seasonal heat storage;
- Presents a synthesis of the calculation elements specific to solar district heating systems with seasonal heat storage, both for the analytical method and TRNSYS;
- Provides mathematical models for seasonal storage tanks: fully mixed tank, stratified tank, and tank implemented in TRNSYS.

The validation of mathematical models describing the thermal behavior of the storage tank introduces the following original contributions:

- Demonstrates the applicability of the fully mixed tank model for indicative investigations conducted over relatively long periods of time;
- Confirms the accuracy of implementing the stratified tank model, both through the analytical method and TRNSYS, as well as CFD, with results compared to several studies in the specialized literature;
- Presents cross-validation of results obtained through three methods: CFD, FDM, and TRNSYS;
- Provides an analysis of simulation times, the appropriateness of each method depending on the context, and the advantages and limitations of each.

Numerical simulation of district heating systems with seasonal heat storage has contributed the following innovations:

- This study is unique in the specialized literature because it combines the analytical method with TRNSYS for solar district heating systems with seasonal heat storage;
- It stands out as the only study that not only validates the results but also presents an analysis of calculation deviations;
- Comparative analysis was conducted on the results using two different climate databases as input parameters;
- The study analyzed variations in a relatively large number of specific parameters, including energies, powers, temperatures, and flows;
- It demonstrated the feasibility of implementing solar heating systems with seasonal heat storage under the climatic and technical conditions in Romania.

The impact of cogeneration in district heating systems introduces the following original contributions:

- It has been demonstrated that cohabitating a district heating system with biomass boilers, along with a cogeneration plant and a heat storage tank, is both feasible and effective under the climatic and technical conditions in Romania;
- Analysis of various parameters over a one-year period was conducted;
- An examination of the annual heat flow within the studied system was performed;

- The enhanced flexibility of the cogeneration system during the summer period was illustrated when integrating the system with a heat storage tank, aligning operational periods with times of high electricity prices.

9. Future directions for further research

After completing the doctoral study, several potential directions for further research have been identified:

- Developing a mathematical model to assess heat losses from the storage tank, considering the inhomogeneous distribution of insulation (varying insulation thickness along the height of the tank);
- Conducting analyses on the use of various types of thermal insulation for seasonal heat storage tanks and determining the optimal insulation thickness;
- Developing and implementing a Life-Cycle Assessment (LCA) model for a solar district heating system with seasonal heat storage;
- Analyzing the reduction of CO2 emissions in the context of utilizing seasonal heat storage in solar district heating systems;
- Creating a mathematical model for the thermal behavior of an underground pit seasonal heat storage system;
- Evaluating the influence of different types of solar thermal collectors on the performance of a district heating system with seasonal heat storage.;
- Conducting an exergetic analysis of a solar district heating system with seasonal heat storage.

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LIST OF PUBLICATIONS

The results obtained in the doctoral research were disseminated in scientific articles, noted with “P”. The citations obtained in articles are noted with “C”. For the publications indexed in WoS are specified the impact factor for 2022, noted with “IF”.

P1. **Hiris, P.D.**, Bode, F., Pop, O.G., Balan, M.C., 2020. Simple Modeling of the Solar Seasonal Thermal Storage Behavior, in: Visa, I., Duta, A. (Eds.), Solar Energy Conversion in Communities. Springer International Publishing, Cham, pp. 21–34 (Scopus). https://doi.org/10.1007/978-3-030-55757-7_2.

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