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External control strategy for Seasonal Thermal Energy Storage

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Abstract:

The paper presents the results of using an external control strategy to optimize seasonal thermal energy storage (STES). Literature studies have been carried out related to design and optimization of the STES. Two STES configurations were considered with adequate constraints. The objective function was defined as minimum operational costs of the entire system. A structural external strategy is proposed which optimizes all heat flows based on the simplex method (Solver(R)). Simulations of system operation were carried out with and without the proposed external strategy for randomly generated outside temperatures in a 5-year horizon.

Keywords:

STES; heat management; dynamic simulation; control strategy

1. Introduction

Rising fuel prices and increasing electricity consumption are driving research into more efficient electricity and heat generation sources [1]. Energy used for space and domestic water heating constitutes 1/3 of the total energy used in industrialized countries like Poland. Fossil fuel consumption and emissions may be reduced by using solar-based technologies. For electricity generation, solar energy may be used directly (PV panels) or indirectly utilizing biofuels [2–4] applying, for example, fuel cell technology which additionally features high efficiency due to the direct transformation of chemical energy into electricity [5–14]. However, the largest market for solar energy is now connected with the absorption of solar radiation into heat up media that are flowing through solar collectors.

Optimization of seasonal thermal energy storage dates to the times when these types of installations were being constructed. According to the design idea a seasonal heat accumulator does not operate separately and is an element of a power system composed of other devices that are typical for the system. The system comprises equipment like solar collectors, heat pumps, conventional gas or solid fuel boilers, pumps, etc. Sometimes, depending on technical conditions, the system may relate to an urban heating network. This creates additional possibilities for altering the amount of heat accumulated in the storage tank and makes the whole system more elastic. It should be noted that, particularly in the case of smaller installations, the urban heating network has an incomparably larger capability of storing heat when compared with the heat accumulator. Considering the set of parameters and external factors influencing the operation of devices and the whole system, a respective operation optimization algorithm for the system seems to be indispensable.

It should consider the specific features of all devices. In addition, it should be matched to the nominal design point of the system when applying it to an existing object or be given the flexibility to select individual devices (their size, operating parameters, etc.) if it is used at the design stage. During optimization particular attention should be focused on the accumulator itself and its interplay with other objects. Devices mentioned earlier that are part of the system, like solar collectors, heat pumps, boilers, etc., are generally commercially available and their operation characteristics and parameters are known. This does not however apply to the storage tank. There are several types of storage [15] that should be taken into consideration. Moreover, insulation plays a vital role here—its thickness, conductivity and above all resistance to ground humidity, which significantly increases the conductivity (this type of storage tank is usually partly or totally immersed in the ground). In the available literature there are few papers that include the optimization of system operation with a storage tank. There are however articles where a significant emphasis was put on optimization of the cooperation between an accumulator and an external network as well as with a co-generation plant, as in [16]. The authors use the commercial Excel (R) environment and the Monte Carlo method to select the optimal size of the accumulator. The analysis was made for three cases: for the cogeneration system electric power of 40 kW, 80 kW and 160 kW. Some authors present modelling methods and optimizing algorithms for storage equipped systems cooperating with a central air conditioning system in public utility buildings [17,18]. This case is somewhat different as cold instead of hot water is stored, but the idea remains substantially similar. The accumulator is charged during the night using cooling units (when electricity prices are lower) and discharged during the day,

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when the cooling demand and electricity prices are higher. The authors analysed 5 operation scenarios for the system: cooling, storage charging, storage charging with operation of cooling units, discharging, discharging with operation of cooling units. It should be mentioned that the storage tank operates diurnally, and not seasonally. In other work [19] operation optimization of the accumulator is performed including economic conditions like variable electricity prices and climate changeability.

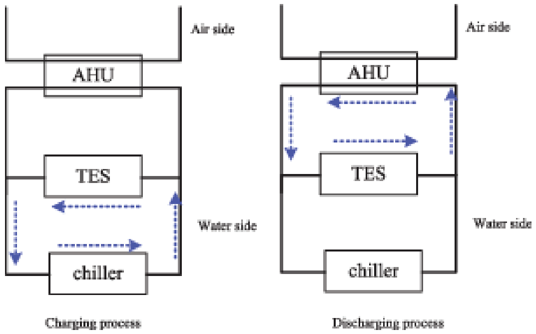


Figure 1: Diagram of charging and discharging processes for a thermal energy storage tank (TES) [18]

In fig. 1 a diagram of the charging and discharging process for a storage tank was presented according to [18]. In the paper, seasonal storage was analysed, where additional parameters considered during the modelling and optimization process were considered, e.g., variable ambient and ground temperatures.

Seasonal heat storage was analysed in the study [20], where the discussed installation was placed in a public utility building with a surface area of 3,700 m2. In contrast to the device investigated in this paper, a UTES (Underground Thermal Energy Storage) equipped with a heat pump was used.

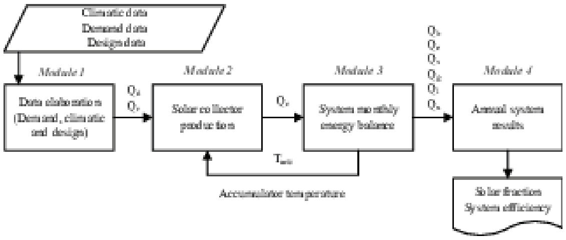


Figure 2: The block diagram used for calculations for the system analysed in [21]

In the paper [21] the authors proposed a simplified method for Central Solar Heating Plants with Seasonal Storage systems. The simplified method was graphically depicted in Fig. 2. Additionally a dynamic analysis of the system in TRNSYS [22] and an economic analysis were done by the authors.

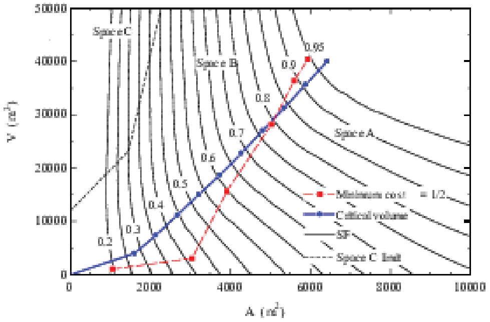


Figure 3: Solar collector area and volume of seasonal storage, isoquant lines of solar fraction [23]

In the same study, an authorial relationship diagram between the storage volume and the solar collector surface area was presented. In the diagram the Space C limit was presented that, according to the analysis made by the authors, is ineffective from the aspect of cooperation between the collectors and the storage tank. The authors also estimated that if the cost of the storage tank alone was decreased by about 50% and the investment costs that need to be borne for solar collectors and other, auxiliary devices, then the introduction of a storage critical volume could become an attractive idea from the economic viewpoint (also shown in the graph).

Table 1: Comparison of methods for modelling seasonal thermal energy storage—yearly characteristics [23]

		Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Input Data	Qr MWh	275	331	440	436	481	486	546	552	464	409	298	257	4978
	H MJ/(m2-day)	6.4	9.8	13.8	17.4	21.5	23.8	25.3	22.5	16.5	11.6	7.5	5.7	
	T °C			10.3		16.7		24.3	23.8	20.7	15.4	9.7	6.5	
	amb	6.2	8.0		12.8		21.0							
	Qd MWh	1309	865	632	366	80	0	0	0	0	142	807	1287	5488
TRNSYS [22]	Qc MWh	165	210	289	289	326	317	335	304	160	143	166	152	2856
	Qg MWh	1130	659	347	162	0	0	0	0	0	0	0	389	2687
	SF %	14%	24%	45%	56%	100%	100%	100%	100%	100%	100%	100%	70%	51%
Lunde [24]	Qc MWh	182	231	316	317	347	332	350	321	229	173	130	146	3075
	Qg MWh	1132	638	320	53	0	0	0	0	0	0	0	359	2501
	Tacu °C	30	30	30	30	39.9	52.2	65.1	76.9	85.0	85.7	59.7	30.0	—
	SF %	14%	26%	49%	86%	100%	100%	100%	100%	100%	100%	100%	72%	54%
BKM [25]	Qc MWh	175	229	313	313	345	329	349	315	217	160	117	134	2996
	Qg MWh	985	647	375	89	0	0	0	0	0	0	0	517	2614
	Tacu °C	31.9	29.1	29.6	30.6	35.6	47.3	59.8	72.1	81.7	85.6	72.4	47.0	—
	SF %	25%	25%	41%	76%	100%	100%	100%	100%	100%	100%	100%	60%	52%
GLS [26][27][28]	Qc MWh	162	210	279	296	349	321	333	287	180	123	72	95	2708
	Qg MWh	1147	655	353	70	0	0	0	0	0	0	0	606	2830
	Tacu °C	29.8	29.7	29.5	29.4	43.4	54.2	69.3	80.5	87.2	82.8	55.3	30.0	—
	SF %	14%	23%	36%	71%	100%	100%	100%	100%	100%	100%	100%	59%	48%

In the study [23] a comparison was made of various modelling methods for systems comprising seasonal thermal energy storage. These methods were used in Engineering Equation Solver [29], which was also used to generate yearly operation characteristics for a system with storage. Except for the simplified method presented by the authors, two others were also analysed. One of them is a 1979 method proposed by Lunde [24,30], and the other from 1981 by Braun, Klein and Mitchell which they named BKF [16]. The list of modelling methods was presented in the Table 1. An integral element of this research was comparison of the results with simulations performed in the previously mentioned TRNSYS software (it is also mentioned in the table 1).

2. Base for calculations

2.1 Optimization method—Solver$^{(R)}$

Optimization of the storage operation was performed using Solver(R) available in Excel(R)environment; detailed information on this topic may be found in [31]. When linear optimization is conducted using Solver a numerical procedure is used called a simplex algorithm [32–35]. The simplex method, first proposed by George Dantzig in 1947, is the first algorithm of numerical optimization developed for the American army and widely used (in many variations) till the present day. The simplex method is basic and universal and enables one to solve all kinds of linear models. This is an analytical method allowing for computing models independent of their size. There are several versions of realizing the simplex algorithm, but, except for different ways of calculating and methods of improving the algorithm convergence, the idea remains unchanged. This method requires however that many calculations be made during the solving of the model and the calculation itself is iterative.

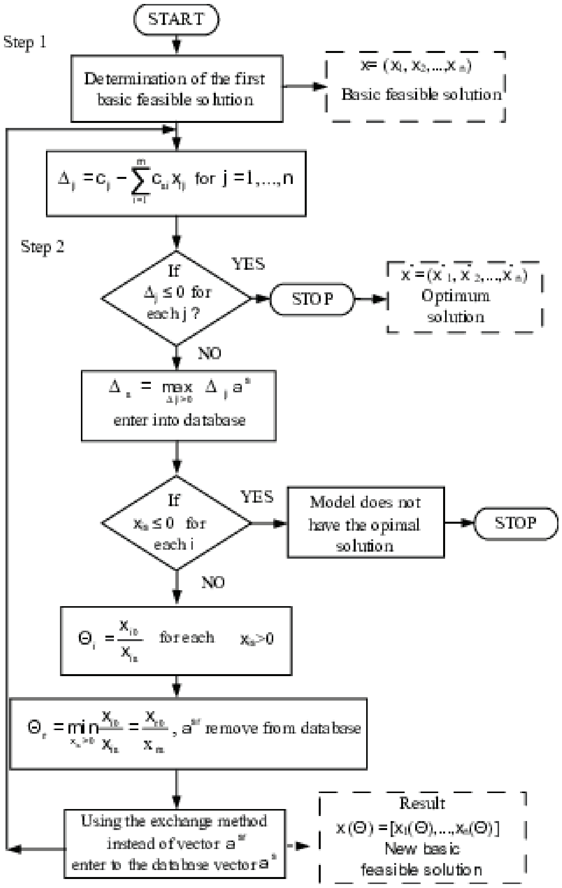


Figure 4: Block diagram of the simplex method (example for a model where the objective function is maximized) [36]

In the simplex algorithm, two basic stages may be distinguished. The first one consists of determination of the basic allowable solution. This may be achieved by introducing additional decision variables into the model. The second stage comprises correction of subsequently performed iterations of the basic allowable solution until an optimal solution is found if the solution exists. The correction of solutions is in fact tantamount to the generation of new basic allowable solutions and checking them from the angle of optimality. The value of the goal function for the subsequent solution (when the objective function is maximized) is often higher than the one before. It is possible that during computations the objective function value will be equal to the objective function value from the previous solution. It may not however be lower. There is a clear analogy in the case of minimizing the objective function. Calculations made with the simplex method have an iterative character. There are two criteria in the method, giving the possibility of terminating calculations and assessing whether the base solution is an optimal one or not; and if not, whether more solutions may be generated. The simplex algorithm is quite labour–intensive, particularly for large–scale models. Computer applications of the algorithm are used to solve such models. Many programs assisting mathematical calculations allow for the development of calculation procedures for the simplex method or are equipped with ready-made simplex modules, like Solver. The simplex method allows one to solve continuous models of linear programming. A block diagram of the method is presented in Fig. 4; in the next iteration of the simplex method the following cases are possible:

- $\Delta_j \le 0$ for every $j = 1, 2, ..., n$ is a basic, allowable solution,

- x_{is} ≤ 0 for every *i* = 1, 2, ..., *n* then the model does not have an optimal solution,
- there exists $\Delta_S > 0$ and there exists $x_{is} > 0$ then a new basic allowable solution may be obtained.

The simplex algorithms make it possible to go from one basic solution to subsequent ones, usually more correct due to the value of the objective function. Iterations are made if the optimal solution is obtained, if it exists. The quantity of iterations that need to be made when solving a model and achieving an optimal solution cannot be precisely specified. It is known that for a set of *n* decisive variables and *m* substantial limiting conditions, the number of base solutions is at a maximum:

$$\binom{n}{m} = \frac{n!}{m! \cdot (n-m)!}$$

The simplex method does not search all the base solutions, merely selected ones. The way of selection is directed. For most cases the algorithm is convergent within a finite number of iterations. From calculation experience it may be concluded that the number of iterations performed is embraced within the limits of the number of substantial limiting conditions to the triple of the number of conditions. Iteration number estimation commonly present in the literature is equal to 2·(*n* + *m*). All the data result mainly from computational experience and are solely estimated values.

It must be noted that the simplex method included in the Solver package is based on differential calculus, which has the effect that for significantly non–linear tasks, it does not give correct results. For this reason, the temperatures in the accumulator were set at 60°C before every optimization (mean value between the extreme values 40/80°C). In the future, methods based for example on artificial intelligence should be used [37–42].

2.2 The objective function

The operation criterion for the optimizer may be an economic function that will, for example, minimize the operating costs of STES operation. Therefore, the optimization goal will be to maximize the profit, which may be understood in different ways. A total profit/loss balance includes many various elements, including income or costs of a typical financial origin. Optimization does not influence these costs and it is not sensible to include them in the optimization process. Optimization influences operating costs. For this reason, the total operating cost in the analysed period will be the objective function, i.e., for periods *n* (from the beginning of calculations), n+1 till periods n+3 or n+6 respectively depending on the selected calculation mode. It may present mathematically as:

$$\mathrm{K_o} = \sum \mathrm{K^i_{Fuel}} + \Delta \mathrm{K_{HeatStorage}} - \sum \mathrm{K^i_{Penalty}} - \sum \mathrm{K^i_{Power}}$$

where: *i* —index of the following calculation steps; $\Delta K_{HeatStorage}$ —cost resulting, and amount of heat accumulated at the beginning and at the end of the analyzed time period (or from the price difference); K_{Fuel} —fuel cost in the subsequent calculation steps; $K_{Penalty}$ —penalty for heat not taken from the collectors; K_{Poweri} —cost of the consumed electricity.

Cost of fuel used for supplying other heat sources in consecutive settlement periods will be calculated as:

$$\mathrm{K^i_{Fuel}} = \mathrm{B^i_{NG}} \cdot \mathrm{k_{NG}}$$

where: B^i_{NG} —use of natural gas in respective calculation step; k_{NG} —unit price of the natural gas.

Cost of electricity supplied to auxiliary devices and the heat pump in consecutive settlement periods will be calculated as:

$$\mathrm{K^i_{Power}} = \frac{\mathrm{Q_{STES}}}{\mathrm{COP_{HP}}} \cdot \mathrm{k_{Power}}$$

where: Q_{STES} —heat taken from the accumulator; COP_{HP}—heat pump COP; k_{Power} —unit price of electricity.

Heat supplied to the buildings must maintain the right temperature level, which may not be achieved directly from the storage tank when its temperature drops below the returning water temperature.

Coefficient of Performance of the heat pump depends on the temperature difference between the upper and lower heat sources and its perfectness (with respect to the Carnot cycle); in the calculations the following relationship was assumed:

$$\mathrm{COP} = \eta_{\mathrm{HP}} \cdot \frac{\mathrm{t_{DH}} + 273.15}{\mathrm{t_{DH}} - \mathrm{t_{STES}}}$$

where: η_{HP} —heat pump perfectness; t_{DH} —temperature of water fed to the heating grid; t_{STES} —temperature in the storage tank.

The heat stream fed to the local heating grid was not optimized. It is not set and is independent of the control system operation. This value is not included in the objective function. The system incorporates a heat storage tank, therefore heat generation is not equal to the heat sale. Heat generation in the period for which forecasts were made may be different than the heat sold. As a result, it is necessary to consider the difference between heat sale and heat generation. Heat prices are not variable in time, so only the total heat difference was included. It will be calculated as the difference between the heat kept in storage at the beginning of the analysed period and the heat at the end. Presented below is the relationship describing the cost resulting from the change:

$$\Delta \mathrm{K}_{\mathrm{HeatStorage}} = (\mathrm{Q}_{\mathrm{Final}} - \mathrm{Q}_{\mathrm{Initial}}) \cdot \mathrm{k}_{\mathrm{HeatStorage}}$$

where: $\Delta K_{HeatStorage}$ —cost of avoided heat sale that was accumulated in the storage tank during the analysed period; Q Begin —amount of heat accumulated at the beginning of the analysed period; Q Final —amount of heat accumulated at the end of the analysed period; $k_{HeatStorage}$ —unitary heat price of the heat accumulated in the storage tank. On the other hand, optimization with the condition that the amount of heat stored at the end must be equal to the heat stored at the beginning may be conducted.

In the period n or n and n+1 storage operation will be optimized by controlling its work so that it will be possible to realize the planned heat production and to recover all the heat generated in the solar collectors. Should the forecasts alter to the extent that it will not be able to balance the production, then the costs of heat generation from other sources or of heat lost that was generated by the collectors will be considered. The objective function contains a penalty element for unrecovered heat from the solar collectors and for over cooling of the storage tank in the following form:

$$\mathrm{Q}^{\mathrm{i}}_{\mathrm{Solar}} > \mathrm{Q}^{\mathrm{i}}_{\mathrm{Plan}} \text{ then } \mathrm{K}^{\mathrm{i}}_{\mathrm{Penalty}} = \mathrm{K}_{\mathrm{Overload}} + \mathrm{k}_{\mathrm{Overload}} \cdot \mathrm{t} \cdot \mathrm{Q}^{\mathrm{i}}_{\mathrm{Overload}}$$

$$Q^{i}_{Overload} = Q^{i}_{Solar} - Q^{i}_{Plan}$$

$$Q^{i}_{Solar} = Q^{i}_{Plan} \text{ then } K^{i}_{Penalty} = 0$$

$$Q^{i}_{Solar} < Q^{i}_{Plan} \text{ then } K^{i}_{Penalty} = k_{Subcooling} \cdot t \cdot Q^{i}_{Subcooling}$$

$$Q^{\{i\}}_{\{Subcooling\}} \;=\; Q^{\{i\}}_{\{min\}} - Q^{\{i\}}_{\{Plan\}}$$

where: Q^{i}_{Solar} —heat recovered from the solar collectors in the ith time interval for current heat forecast; Q^{i}_{Plan} —heat supplied to consumers in the i th time interval resulting from the forecast; $K^{i}_{Penalty}$ —penalty value; t —length of the time interval, month, week, day, hour; $k_{Overload}$ —coefficient of the penalty function for heat overproduction; $k_{Subcooling}$ —coefficient of the penalty function for heat underproduction (cost of heat supplied to the storage tank from auxiliary sources); Q^{i}_{min} —minimum of heat kept in storage; $Q^{i}_{Overload}$ —heat not recovered from the collectors in the ith time interval.

Table 2: Objective function parameters for optimization processes

Parameter	Value*	Comment
kNG, EUR/GJ	12	cost of natural gas fed to the central heating boiler
kPower, EUR/GJ	44	cost of electricity supplied to the heat pump
kSubcooling, EUR/GJ	kNG	heat of additional heating of water in the boiler by a gas/coal boiler/heating grid or/and the heat pump
kOverload, EUR/GJ	6.0	cost of heat lost, full storage charging at positive balance of heat production from the collectors and heat demand

*at conversion rate EUR/PLN=4.2

Table 2 contains selected coefficients used in the developed objective function. The coefficients may vary depending on the season of the year and geographic location (country) as well as local conditions. The cost of natural gas supplied to the central heating boiler was calculated on the assumption that boiler efficiency was 80% and the gaseous fuel tariff was according to [43]: w-5 (gas) and E-1A (distribution) after PGNiG S.A. (in total 1.3678 PLN/Nm3); LCV was assumed to be 35 MJ/Nm3.

The cost of electricity supplied to the heat pump was assumed to be equal to the value mentioned in [44]—one–zone tariff C11 (“Simplest for your company”) after RWE Poland S.A. (0.6587 PLN/kWh). Heat lost in the case when the storage tank is fully charged and the collector heat production exceeds the amount of heat consumed was calculated for Hewalex KS2000 TP AC flat collectors [45]. The net price for this device is 151.04 EUR per m2 of working surface. It was assumed that the lifetime of solar collectors ranges from 15 to 25 years [46]. The cost of lost heat was calculated on the assumption that the collectors will work for 15 years (safer variant). All the above costs as well as other parameters and results presented in this work were determined using the currency conversion rate of PLN 4.2 = 1 EUR.

The presented methodology is also valid for other—not necessarily cost balance based—criteria. These could be the CO2 emission criterion [47,48], minimization of fossil fuel consumption or the idea of energy storage of external origin (e.g. at low electricity prices, which might even be negative as a Danish example showed).

2.3 Limitations

Optimization limitations

1. Water temperature in the storage tank: 40 .. 80C
2. Maximum storage charging/discharging rate, Δt_{STES}/month
3. Maximum heating power of the grid, Q_{DH}/month
4. Maximum heating power of the solar collectors, Q_{Solar}/month
5. Maximum heating power of the gas boilers, Q_{Boiler}/month

Except for limitations regarding the sole optimization process, the system model contained internal constraints not allowing the overheating or over-cooling of the storage tank, ti.e. it did not allow t_{values} outside of the range of 40 .. 80°C, however shut-off of those limitations was also possible.

2.4 Analysed case

To determine the possibility and test the proposed solutions a structure containing all typical devices cooperating with seasonal heat storage tanks was selected. Hence, the analysed system contained the following elements:

- flat solar collectors [45]
- heat pump of COP 3.5 [49]
- fossil fuel boilers (natural gas)

a: Variant I b: Variant II

Figure 5: Tentative depiction of both analysed variants

Two configuration cases for the whole system were considered:

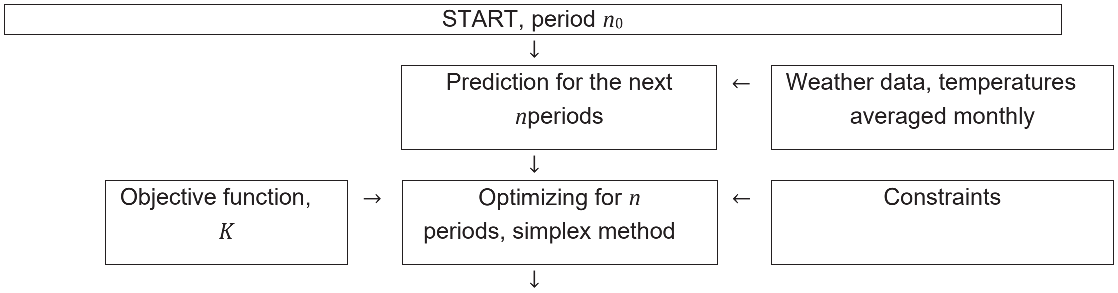
1. Variant I, where the collector area was selected in such a way that their heat production corresponded to 100% of the heat demand in a yearly cycle—heat losses from storage were not covered by solar energy.
2. Variant II, where STES had to cover 100% of the heat demand and the solar collector area was chosen so that it also covered the heat losses from the accumulator.

Both cases differ in collector size and the heat capacity of the storage tank—see fig. 5.

3 Optimizing algorithm for the Seasonal Thermal Energy Storage system

3.1 Description of the main algorithm

A structural (hierarchical) optimizing algorithm is proposed for a Seasonal Thermal Energy Storage system. Based on the algorithm several layers cooperate with each other to obtain a solution of the previously defined problem.



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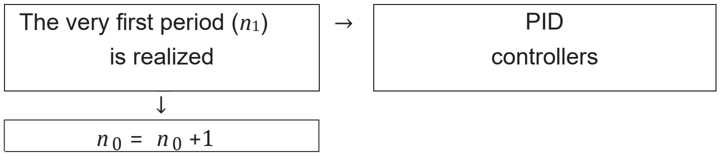

Figure 6: Optimizing algorithm for STES

Fig. 6 presents a block diagram of the proposed optimizing algorithm for STES. In the very first step, the prediction of heat consumption for the next n periods (e.g., 11 months) is made. The prediction may be based on forecast weather, temperatures, etc.; in the calculations randomly generated temperatures at the average level for Warsaw are used. Based on the forecast heat consumption and possible heat production/accumulation, the optimizing process is utilized for the chosen objective function while fulfilling the given limitations.

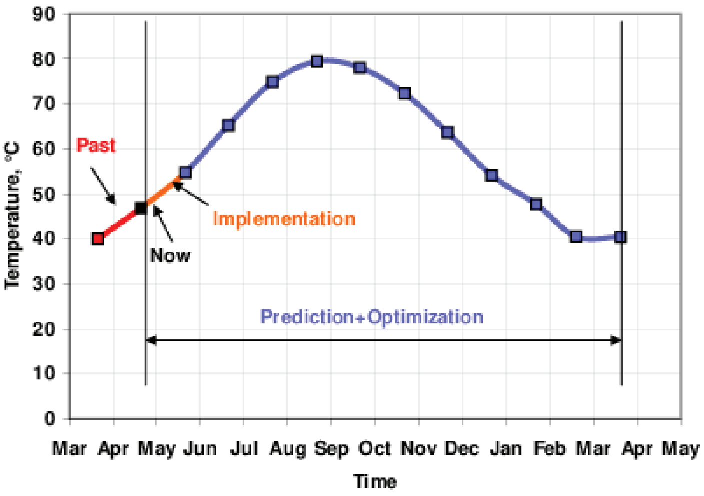

Figure 7: An example of utilization of the optimizing algorithm

Based on the obtained operational line for the next n periods (11 months), only the very first period is really done—see Fig. 7—and adequate PID controllers are set to fulfil the ending point. The rest of the operational line is deleted and no longer considered, but the whole process is repeated.

3.2 Choosing a design point of the system

The optimizing procedure regards the current period and next n periods (e.g., 11 months, so it is possible to use the algorithm to determine a design point for the whole system (solar collector area, water tank volume, etc.) based on the chosen/known heat consumption profile and averaged monthly weather data.

- In this case, the optimizing algorithm needs to be supplemented by two independent variables:
- solar collector area in relation to heated area, m2/m2
- water tank volume in relation to heated area, m3/m2

Table 3: Design point parameters chosen during the optimizing processes

Parameter	Case I	Case II
Heated area, m2	100	100
Solar collector area, m2	17	25
Tank volume, m3	70	102
Objective function value, EUR/a	113	52

By utilizing the optimizing algorithm, the design point parameter of the STES system was found as well as the temperature distribution during the year. (see Table 3).

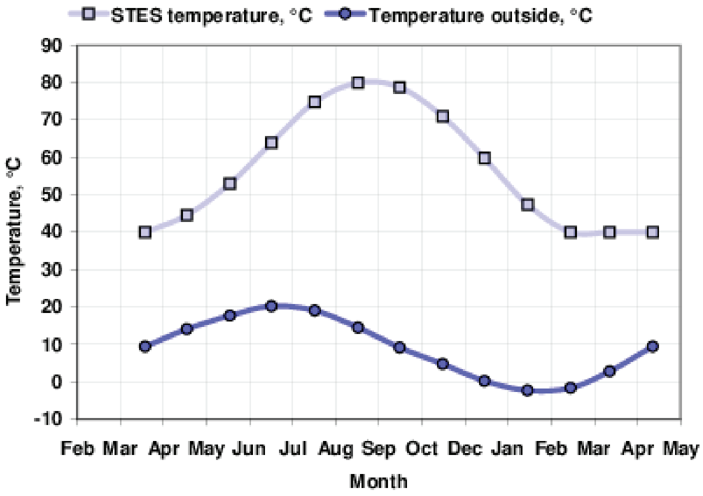

Figure 8: Monthly averaged temperatures distribution at the design point for Case I

Fig. 8 presents the temperature forecast at the design point, and related water temperatures in the tank.

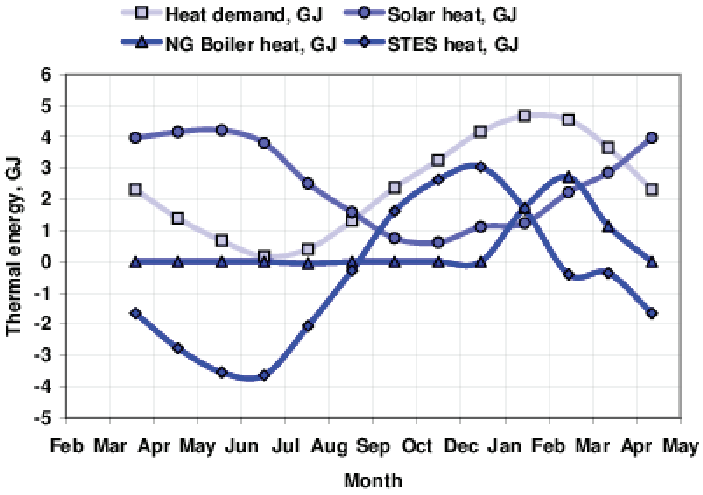

Figure 9: Heat generated by the system elements at the design point for Case I

Fig. 9 presents the amount of heat generated by the system elements in order to cover heat demand at the design point and chosen heat consumption profile. The negative values of heat fluxes denote that the charging process of the STES tank is in progress.

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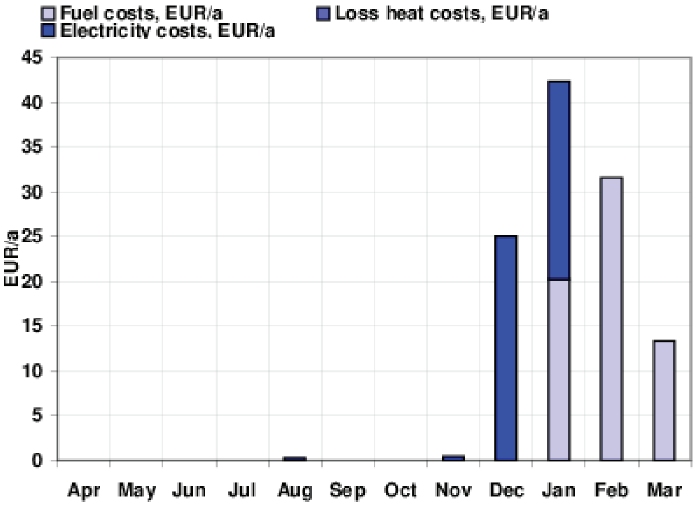

Figure 10: Objective function at the design point for Case I

At the design point for Case I, the value of the objective function is 113 EUR/a (for 100 m2); specific components of the function are presented in Fig. 15, the highest cost is electricity delivered to the heat pump in the periods when the water temperature in the tank falls below 60○C, the second highest cost is the fuel used in the boilers to cover heat demand when there is a fully discharged heat storage tank.

4 Conclusions

An external control strategy and optimizing algorithms are proposed for supporting the STES operation.

Table 4: Summary of all analyzed scenarios

Parameter	Case I limited	Case I optimized	Case II	Case II limited	Case II optimized
Averaged yearly costs, EUR/a	113	109	52	60	57
Water tank volume, m^3	70	70	102	102	102
Solar collector area, m^2	17	17	24	24	24
Minimum water temperature, °C	40	40	36	40	40
Maximum water temperature, °C	80	80	84	80	80
Maximum charging speed, GJ/month	3.8	3.9	5.3	5.3	5.3
Maximum discharging speed, GJ/month	3.3	3.3	3.4	3.4	3.0
Maximum heat produced by Natural Gas boiler, GJ/month	3.9	3.8	–	1.3	1.1
Maximum heat produced by solar collectors, GJ/month	4.2	4.2	5.8	5.8	5.8
Maximum heat demand, GJ/month	5.2	5.2	5.2	5.2	5.2

Table 4 presents a summary of all analyzed cases. The operating costs of systems with smaller sized devices (solar collectors by 41%, and water tank volume by 45%) are two times smaller than for the bigger sized system. Profits from utilization of the external control strategy are relatively small, on level 4...5%. Apart from economic profits, using the proposed external control strategy lowers the maximum heat produced by the natural gas boiler in the range 3...18%.

Use of the external control strategy does not provide spectacular profits, but theoretically a huge water tank can be run without any control system merely by applying a simple regulation system.

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